PENN PRAXIS/THE ARCHITECTURAL CONSERVATION LABORATORY

GEORGE NAKASHIMA
ARTS BUILDING AND CLOISTER
CONSERVATION & MANAGEMENT PLAN

APPENDICES

GEORGE NAKASHIMA
ARTS BUILDING AND CLOISTER
CONSERVATION & MANAGEMENT PLAN

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School of Design
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Modeling and Analysis of Plywood Plate Structure, Master’s Thesis for Advanced Masters in Structural Analysis of Monuments and Historical Constructions (SAHC). Andi Troci, Czech Technical University in Prague, 2016.

ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Andi Troci

Modeling and Analysis of Plywood Shell Structures.

This Masters Course has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Czech Republic | 2016

DECLARATION

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Title of the Msc Dissertation: Modeling and Analysis of Plywood Shell Structures

Supervisor(s): Petr Kabele and David Biggs

Year: 2016

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University: Czech Technical University in Prague

Date: July 10, 2016

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CZECH TECHNICAL UNIVERSITY IN PRAGUE
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MASTER'S THESIS PROPOSAL

study programme:	Civil Engineering
study branch:	Advanced Masters in Structural Analysis of Monuments and Historical Constructions
academic year:	2015/2016

Student's name and surname:	Andi Troci
Department:	Department of Mechanics
Thesis supervisor:	Petr Kabele and David Biggs
Thesis title:	Modeling and analysis of plywood shell structures
Thesis title in English	see above

Framework content: The aim of the thesis is the structural studying of the Nakashima's hypper roof shell in New Hope, Pennsylvania. The structure of the thesis is organized as following:

-Theory of shallows shells
- Simplified designing methods
- Analytical solutions and verification of the numerical model
- Sensitive analysis of the structure for different load cases and boundary conditions

Assignment date: 16/04/2016 Submission date: 10/07/2016

If the student fails to submit the Master's thesis on time, they are obliged to justify this fact in advance in writing, if this request (submitted through the Student Registrar) is granted by the Dean, the Dean will assign the student a substitute date for holding the final graduation examination (2 attempts for FGE remain). If this fact is not appropriately excused or if the request is not granted by the Dean, the Dean will assign the student a date for retaking the final graduation examination, FGE can be retaken only once. (Study and Examination Code, Art 22, Par 3, 4.)

The student takes notice of the obligation of working out the Master's thesis on their own, without any outside help, except for consultation. The list of references, other sources and names of consultants must be included in the Master's thesis.

Master's thesis supervisor Head of department

Date of Master's thesis proposal take over: July 2016

Student

This form must be completed in 3 copies – 1x department, 1x student, 1x Student Registrar (sent by department)

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Finally, to my parents and my sister for their never ending support.

Andi Troci

ABSTRACT

The main objective of the present thesis is to assess the static state and capacity of the roof at Nakashima Arts Building in Pennsylvania, U.S.A. The load carrying structure of the roof is a plywood hyperbolic paraboloid shell.This dissertation is a continuation of previous and ongoing studies of the Nakashima Arts Building, in which geometrical and damage survey was performed.

First, the theory of shallow shells is reviewed. Simplified statics and analytical solutions of hyperbolic paraboloid shells are developed for structural models with the same dimensions as the Nakashima Arts Building roof. The same structures are then analyzed by the finite element method (FEM) with program ADINA. Comparison of the results allows us to discuss the accuracy and limitations of the simplified and analytical solutions, as well as to verify the FE model.

Secondly, numerical analyses by FEM are carried out with the aim to understand the complex behavior of the Nakashima Arts Building roofstructure. Considering different configurations of boundary conditions and load cases allows us to determine and localize the vulnerabilities of the structure. Through these results it will be possible to focus inspection to the areas indicated as vulnerable and to adjust maintenance plans. Moreover, it is suggested to perform a measurements campaign of the roof deflection in winter time, when the snow load is acting, in order to compare deflections with the numerical results. This will allow further validation and refinement of the model.

ABSTRAKT

Hlavním cílem této diplomové práce je posoudit statický stav a únosnost střechy budovy NakashimaArtsBuildingv Pennsylvanii, U.S.A. Nosnou konstrukci střechy tvoří překližková skořepina ve tvaru hyperbolického paraboloidu (HP). Tato disertace navazuje na předchozí a probíhající průzkum budovy Nakashima ArtsBuilding, ze kterého byly získány informace o geometrii konstrukce i jejím stávajícím stavu poškození.

Nejprve je zpracována rešerše teorie mělkých skořepin. Zjednodušené statické řešení a analytické řešení jsou provedeny pro HP skořepiny stejných rozměrů, jako je střecha na NakashimaArtsBuilding. Tyto konstrukce jsou pak analyzovány metodou konečných prvků (MKP) v programu ADINA. Porovnání výsledků nám umožňuje nejen diskutovat přesnost a omezení zjednodušeného a analytického řešení, ale také verifikovat konečněprvkový model.

Následně jsou provedeny analýzy MKP, jejichž cílem je porozumět komplexnímu chování střešní konstrukce NakashimaArtsBuilding. Při uvážení různých okrajových podmínek a zatěžovacích stavů jsou identifikována a lokalizována slabá místa konstrukce. Tyto výsledky mohou posloužit k zacílení inspekčních prací na náchylné části konstrukce a k úpravě plánu údržby. Navíc je navrženo, aby bylo provedeno měření průhybů konstrukce v zimním období, kdy je zatížena sněhem. Porovnání změřených průhybů s výsledky numerických výpočtů umožní další validaci a zpřesnění modelu.

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1. INTRODUCTION

1.1 Shells, Special Structures

The shell structures have always been a clear proof of engineering abilities. Their first expression was through the dome shape. The Pantheon in Rome, built in 125 AD. still impresses for its dimensions and technology. It consists in a semispherical dome with a diameter of 43.3 m over a 6.4 m thick drum wall. It is still nowadays one of the largest dome structure in the world. This is what makes this structures so interesting and fascinating. Their dimensions seems to defy the physics laws and encourage engineers and architects to dare more in the development of their shape. Before the twentieth century, this structures were considered to be weighty and large perimeter walls were needed to support the high horizontal thrusts.

Figure 1.1 – Pantheon, Rome

(www.didatticarte.it)

Figure 1.2 - Zeiss Planetarium, Jena

(www.zendome.de)

The development of the new material reinforced concrete, became and inspiration for this type of structure, since it became possible to have thin shells with large spans. One of the first examples of this thin shells is Zeiss Planetarium in Jena (Germany). What makes this structure particularly relevant is the thickness of just 60 mm for a span of 25 m. Understanding the potential of this type of structure and of the new material the dome shape started to be considered as restrictive and new shell structures with double curvature were constructed. Pier Luigi Nervi, Eduardo Torroja and Felix Candela were pioneers of these new forms, crating structures extremely light and beauty. In the forties the theory of shells was well established and the development of the computers allowed to derive and verify solutions for very slender and shallow shells.

In a continuous process of innovation, in the fifties the timber shell structures started to became popular. Two representative structures are: the Forest Products Pavilion in Oregon and the four hyperbolic paraboloid timber shell roofs of the Former Silhouette Factory. This two examples show that timber was the pioneer of the hyper roofs.

Figure 1.3 – Nervi: Sport building, Rome (www.pinterest.com)

Figure 1.4 - Torroja: Zarzuela's Hippodrome, Madrid (www.archidose.blogspot.com)

Figure 1.5 - Candela: Los Manantiales, Mexico City (www.archdaily.com)

Figure 1.6 - Forest Products Pavillon, Portland (www.bonniehull.net)

Figure 1.7 - Factory for Silhouette Coursette, Market Drayton (www.architecture.com)

The advantages (efficiency on use of the material, elegance, large spans) introduced by this structure, have been hampered by the expansive and elaborate work required to build the formwork of the shell. Moreover, the deep understanding of their structural behavior was limited by the complex mathematical equations involved in the designing and analysis of these complex shapes.

From the first applications, timber showed to be a suitable material for this type of structures, since it is a flexible, workable and a sustainable material. Nowadays, many research projects have been carried out with the aim of understanding and improving the structural behavior of this material. Moreover, in the last 30 years the concept of sustainable buildings has increased its importance becoming nowadays an essential feature of every new building.

The fully understanding of shell structures behavior is not yet reached and history of civil engineering has repeatedly shown that new types of structures have been built before their behavior was fully understood (Bradshaw et al., 2002).

The development of the FEM concept, the free forms of the modern architecture and the concept of sustainable buildings encouraged nowadays the studying of the behavior of the timber shells structures. The increasing of their applications can be possible only through a process of knowledge of their behavior and the development of a clear design process to be followed. This is what motivates the work of this thesis, which is meant to be part of this development process.

1.2 Scope and Objective

The work is developed in such a way that two main objectives represent the thesis' goal. Those two objectives are different but strictly related one with the other. The first consist of an important path of literature survey with the aim of developing a deep knowledge of the theory that governs the shells behavior. Through the study of the theory, an analytical solution is to be performed and to be later compared with the numerical model in the ADINA software.

Furthermore, the design of the shell structures is a complex process since their performance depends on many factors, from the shape to the material and boundaries. Therefore, in the seventies, when shells reached the peak of popularity, simplified designing rules were developed. Subsequently, a process of comparison between this simplified design rules and the FE analysis is carried out with the aim of verifying their accuracy and applicability.

The second objective of the thesis is the structural assessment of the Nakashima Arts Building under different boundary conditions and load cases. The study is focused on the plywood shell roof and is done through the numerical model developed by the ADINA software. The intention of this second objective it to study of the effects of different boundary conditions and load cases. Note that this study is strictly related with the first objective explained above because is carried out only after the process of verification of the FE model.

As mentioned above the structural assessment concerns the Nakashima Arts Building which is characterized by a unique architectural style where the Japanese craft traditions are combined with the modern influences. The Arts Building was built between 1964 and 1967 by George Nakashima in New Hope, Pennsylvania. The architect's ability is reflected in the roof of this building, which is a hyperbolic paraboloid surface made by three layers of plywood. The projected shape of the roof is a 10,67 meters wide square. The hyperbolic paraboloid shape is obtained by lifting one corner of 4.27 meters. The Figure 1.9 shows the principal dimensions of the roof structure, while FIGURE shows the west elevation of the Nakashima Arts Building.

Figure 1.8 - West elevation of Nakashima Arts Building (www.nakashimawoodworker.com)

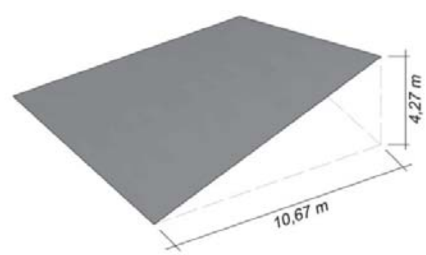


Figure 1.9 - Dimensions of the roof structure

This structure is a living documentation of shells popularity in the United States in the 1950's to 1970's. Its historical importance needs to be preserved and this thesis aims to help in the definition of the restoration and strengthening work to be done.

2. THEORY OF SHALLOW SHELLS – DONNELL THEORY

Shells are structure who's behave depending on the interaction between geometrical and mechanical properties. They are also often described as structure that resist through the shape. The shell geometry has the major influence on how the shell behave, if only in-plane behavior or also out-of plane behavior (Peerdeman, 2008).

As discussed in the Introduction, plywood hyppar roofs can be analyzed by means of the elastic theory of thin shells. In this study, we use the Donnell theory, which takes into account both membrane and bending effects. Basic components of the theory are reviewed hereafter. The review is based on a book by Johan Blaauwendraad and Joroen H. Hoefakker (Blaauwendraad and Hoefakker, 2014)

The well known theory of thin shells in this case needs to be extended in order to take into account both the membrane and bending behavior of shells type as the roof of Nakashima Arts Building. The theory which considers the both behaviors has been developed by Donnell (Donnell, 1933) and is applicable to shallow shells like roofs shells.

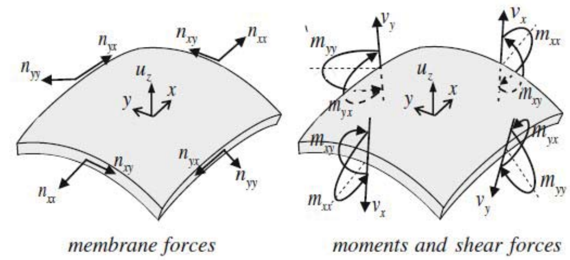


Figure 2.1 – Forces and moments on a shell element of arbitrary curvature **(Blaauwendraad and Hoefakker, 2014)**

In this theory a coupling occurs between the membrane action and the bending action and the aim is to obtain a differential equation which takes into account the coupled states. The difference between the global axis X,Y,Z to describe the geometry of shell and the local axis x,y,z in the shell surface with z normal to the surface is neglected, and this I permitted if the slope of the roof is sufficiently small. Moreover the deformation due to transversal shear is neglected. The Figure 2.1 shows the notation and sign convention for forces and moments.

In the following the relations between displacements, deformations, shell forces and external loads (Figure 2.2) are treated.

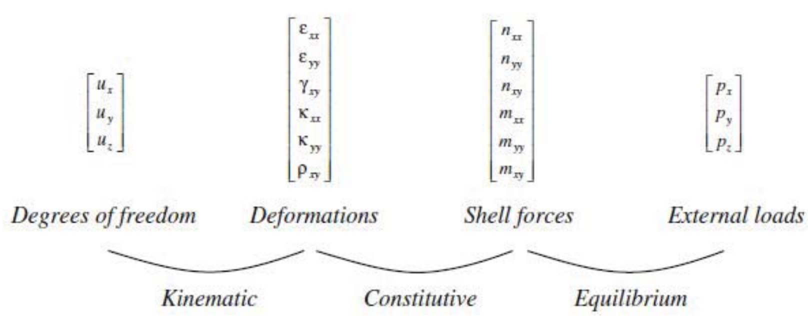


Figure 2.2 - Scheme of relationships for a shell (Blaauwendraad and Hoefakker, 2014)

2.1 Analytical Description of the Shell Surface

The shell's geometry is defined by the shape of the middle surface and the distribution of the thickness along the shell. Their shapes can be distinguished in two main groups: developed and undeveloped surfaces. A developed surface can be deformed into a plane shape without adopting any cut, instead for an undeveloped surface the transformation into a plane shape is possible only by cutting or stretching its middle surface. The geometry of the shell is obtained in three different ways and the way defines the type of the surface.

- Surfaces of Revolution: this surfaces are obtained by the revolution of a plane surface about an axis. An example of surface of revolution is the dome.
- Surfaces of translation: this surface is obtained by sliding a plane curve along another plane curve. The generator is the curve on which is applied the sliding process. The cylindrical surface or the hyperbolic paraboloid surface are obtained through this process.
- Ruled surfaces: this surfaces are obtained by the movement of a straight line through space. Examples of ruled surfaces are the conoid or the hyperbolic parabolid.

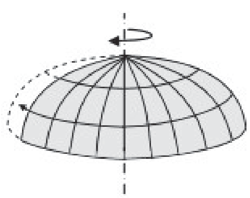


Figure 2.3 – Surface of Revolution: Dome (Blaauwendraad and Hoefakker, 2014)

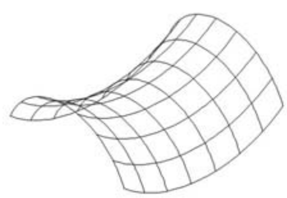


Figure 2.4 - Surface of translation: Hyperbolic paraboloid

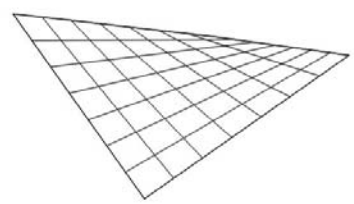


Figure 2.5 Ruled surface: Hyperbolic paraboloid

This thesis is focused more on the hyperbolic paraboloid shapes obtained as ruled surfaces. The equation that describes this surface is the following:

$$z = \frac{x\,y}{L1\,L2}h = \frac{x\,y}{a} \qquad (1)$$

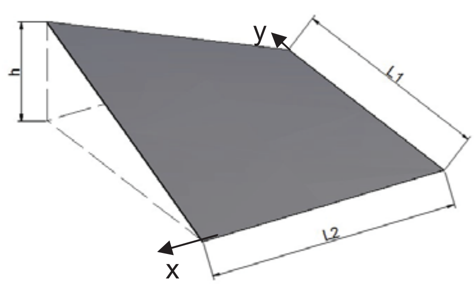


Figure 2.6 – Hyperbolic paraboloid

The intersections of this surface with vertical planes x=const or y=const are straight lines, meaning that the curvature along x and curvature along y are zero. The quantity 1/a represent the twist of the surface $\frac{\partial^2 z}{\partial x \partial y}$ and for this type of surface the twist is constant.

$$\frac{1}{a} = \frac{\partial^2 z}{\partial x \partial y} = \frac{h}{L1\,L2} \qquad (2)$$

2.2 Kinematic Relations

The kinematic relations between the membrane strains and the tangential displacements u_x and u_y (3) are the same as the description for a plate loaded in its plane.

$$\varepsilon_{xx} = \frac{\partial U_x}{\partial x}; \qquad \varepsilon_{yy} = \frac{\partial U_y}{\partial y}; \qquad \gamma_{xy} = \frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x} \tag{3}$$

In case of curved shell and twisted shells the effects of the normal displacements have to be taken into account.

Considering an infinitesimal shell element in the plane x-z as shown in the Figure 2.7 the inclination is defined as $\varphi_x = -\partial z/\partial x$ and the incremental change of the inclination over the distance dx will be:

$$d\varphi_x = -\frac{\partial^2 z}{\partial x^2} dx \tag{4}$$

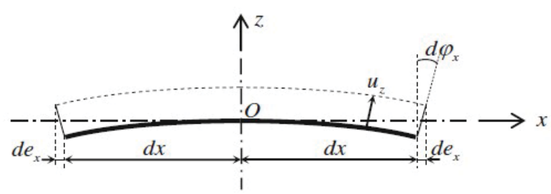


Figure 2.7 - Effect of displacement u_z in curved shell surface

(Blaauwendraad and Hoefakker, 2014)

The change of length due to normal displacement is $de_x = u_x d\varphi_x$ and the strain is defined as

$\varepsilon_{xx} = \frac{de_x}{dx}$. From these two expressions and the eq. (4) the strain in the middle surface will be:

$$\varepsilon_{xx} = -k_x u_z \tag{5}$$

where k_x is the curvature and its expression is:

$$k_x = \frac{\partial^2 z}{\partial x^2} \tag{6}$$

The same considerations done in the plane Y-Z lead to the strain ε_{yy} in the middle surface (7).

$$\varepsilon_{yy} = -k_y u_z; \qquad k_y = \frac{\partial^2 z}{\partial y^2} \tag{7}$$

The effect of the normal displacement in terms of shear strain γ_{xy} has to be evaluated in the infinitesimal twisted shell part as shown in the Figure 2.8. The inclinations have the same expression as previously defined $\varphi_x = -\partial z/\partial x$ and $\varphi_y = -\partial z/\partial y$. The incremental changes $d\varphi_x$ in y-direction and $d\varphi_y$ in x-direction are:

$$d\varphi_x = -\frac{\partial^2 z}{\partial y \partial x}\, dy; \qquad d\varphi_y = -\frac{\partial^2 z}{\partial x \partial y}\, dx \tag{8}$$

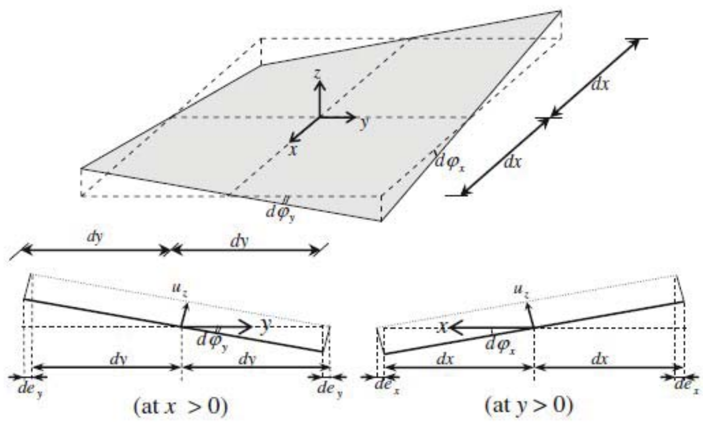


Figure 2.8 - Effect of normal displacement uz in twisted shell surface

(Blaauwendraad and Hoefakker, 2014)

For a continuous surface the two mixed derivatives (8) are equal to each other and the changes of length due to u_z are:

$$de_x = d\varphi_x u_z \qquad de_y = d\varphi_y u_z \tag{9}$$

the related strains $\mathcal{E}_{xy}$ and $\mathcal{E}_{yx}$ are:

$$\mathcal{E}_{xy} = \frac{de_x}{dy} \qquad \mathcal{E}_{xy} = \frac{de_y}{dx} \tag{10}$$

As the shear strain is defined $\gamma_{xy} = \mathcal{E}_{xy} + \mathcal{E}_{yx}$ and considering a continuous surface where the two mixed derivatives of the incremental changes of the rotations are equal we obtain:

$$\gamma_{xy} = -2k_{xy}u_z \tag{11}$$

where k_{xy} is defined as the mixed second curvature of the middle surface

$$k_{xy} = \frac{\partial^2 z}{\partial y \partial x} \tag{12}$$

The equations defined above are associated to the membrane behavior. Concerning the bending behavior the rotations of a flat plate applied to a thin shell of arbitrary curvature with infinitesimal length of arc *dx* and *dy* are:

$$\varphi_x = -\frac{\partial u_z}{\partial x}; \quad \varphi_x = -\frac{\partial u_z}{\partial x} \tag{13}$$

and the bending deformations are represented by the following relations:

$$K_{xx} = \frac{\partial \varphi_x}{\partial x} = \frac{\partial^2 u_z}{\partial x^2}$$

$$K_{yy} = \frac{\partial \varphi_y}{\partial y} = \frac{\partial^2 u_z}{\partial y^2} \tag{14}$$

$$\rho_{xy} = \frac{\partial \varphi_x}{\partial y} + \frac{\partial \varphi_y}{\partial x} = -2\frac{\partial^2 u_z}{\partial x \partial y}$$

Through these relations describing the effect of the normal displacement and rotations it is possible to write the kinematic relations:

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \kappa_{xx} \\ \kappa_{yy} \\ \rho_{xy} \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & -k_x \\ 0 & \frac{\partial}{\partial y} & -k_y \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & -2k_{xy} \\ 0 & 0 & -\frac{\partial^2}{\partial x^2} \\ 0 & 0 & -\frac{\partial^2}{\partial y^2} \\ 0 & 0 & -2\frac{\partial^2}{\partial x \partial y} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}. \tag{15}$$

2.3 Constitutive Relations

The link between stresses and strains is described by the constitutive relations which depend on the material properties (e.g. elastic or plastic). Material properties can also vary in the stress-strain path in a linear or non linear way. Moreover, it can show different behavior in different directions (e.g. wood - anisotropic material, metal – isotropic material). All those properties depend on the type of material and its micro-structure. In structural analysis the real properties of the material are described by the constitutive model and it has to be carefully defined in order to describe in the best way possible the real behavior of the structure.

The following constitutive relations describe a linear elastic and isotropic behavior of the material. For this type of material the stress-strain relation is unique and independent of stress and strain history and it obeys the Hooke's law.

$$\begin{bmatrix} n_{xx} \\ n_{yy} \\ n_{xy} \\ m_{xx} \\ m_{yy} \\ m_{xy} \end{bmatrix} = \begin{bmatrix} D_m & vD_m & 0 & 0 & 0 & 0 \\ vD_m & D_m & 0 & 0 & 0 & 0 \\ 0 & 0 & D_m\left(\frac{1-v}{2}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & D_b & vD_b & 0 \\ 0 & 0 & 0 & vD_b & D_b & 0 \\ 0 & 0 & 0 & 0 & 0 & D_b\left(\frac{1-v}{2}\right) \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \kappa_{xx} \\ \kappa_{yy} \\ \rho_{xy} \end{bmatrix} \tag{16}$$

where:

- D_m: membrane rigidity ($D_m = \frac{Et}{(1-v^2)}$)
- D_b: flexural rigidity ($D_b = \frac{Et^3}{12(1-v^2)}$)
- E : Young's modulus
- v : Poisson's ratio
- t : shell thickness
- n: force per unit length ($n = \frac{\sigma}{t}$)

2.4 Equilibrium Equations

These equations are obtained by considering the equilibrium of the incremental forces along x, y and z direction (Figure 2.1). The two equilibrium equations along x and y direction are the same as for a flat plate loaded in-plane:

$$\begin{gathered} \frac{\partial n_{xx}}{\partial x} + \frac{\partial n_{yx}}{\partial y} + p_x = 0 \\ \frac{\partial n_{xy}}{\partial x} + \frac{\partial n_{yy}}{\partial y} + p_y = 0 \end{gathered} \tag{17}$$

Concerning the out-of-plane equilibrium there are three factors that influence in its definition regarding shells of arbitrary curvature. The first influence is the effect of curvature and due to this the normal stresses n_{xx} and n_{yy} will have vertical components depending on the ratio of curvature. Considering a shell strip of unit width and length dx (Figure 2.9) the vertical component of the n_{xx} is $n_{xx}d\varphi_x$. This lead to the following equilibrium equation:

$$p_z dx - n_{xx} d\varphi_x = 0 \tag{18}$$

Dividing the equation (17) by *dx* and considering the relations (4) and (6) the equilibrium equation become:

$$k_x n_{xx} + p_z = 0 \tag{19}$$

$$k_y n_{yy} + p_z = 0 \tag{20}$$

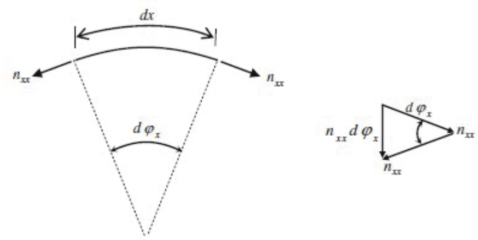


Figure 2.9 - Vertical component of the membrane force n_{xx}

(Blaauwendraad and Hoefakker, 2014)

The equation (20) is obtained in the same way considering a shell strip of unit width and length *dy.*

The effect of twist is related with the membrane shear forces. The shear membrane force n_{xy} acts over the *dy* edge in the y-direction and its vertical component is due to the inclination along the y direction $n_{xy}d\varphi_y$ (Figure 2.10). The same consideration leads to the vertical component of n_{yx} as $n_{yx}d\varphi_x$.

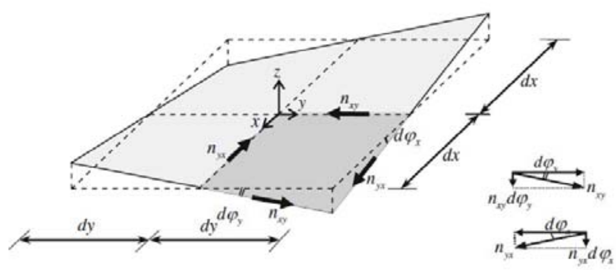


Figure 2.10 - Contribution of shear membrane forces in the equilibrium along z

(Blaauwendraad and Hoefakker, 2014)

The equilibrium equation along the z-direction is:

$$p_z dxdy - (n_{xy} d\varphi_y)dy - (n_{yx} d\varphi_x)dx = 0 \tag{21}$$

Substituting the equations (8) and (12) in the equation (21) and dividing by *dxdy* the equation becomes:

$$2k_{xy} n_{xy} + p_z = 0 \tag{22}$$

The last fact that influences the equilibrium along the z-direction is the bending behavior as it generates the transverse shear force. Considering the system of stresses and bending moments intensities per unit length in x and y, defined in the Figure 2.11, the equilibrium of moments in the x-direction is given by the integral (23).

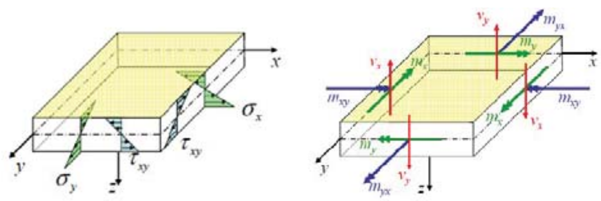


Figure 2.11 - Reference system of stresses and bending moments intensities per unit length (Petr Kabele, SAHC lectures, 2016)

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} (\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}) z dz = 0 \tag{23}$$

Considering that the integrals of $\sigma_x z$ and $\tau_{xy} z$ over the thickness *dz* represent respectively m_{xx} and m_{xy}, the equation (23) becomes the equation (24) and the equation (25) is obtained through the same considerations.

$$\frac{\partial m_{xx}}{\partial x} + \frac{\partial m_{xy}}{\partial y} = -\int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{\partial \tau_{xz}}{\partial z} z dz = v_y \tag{24}$$

$$\frac{\partial m_{yy}}{\partial y} + \frac{\partial m_{xy}}{\partial x} = -\int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{\partial \tau_{yz}}{\partial z} z dz = v_y \tag{25}$$

The vertical equilibrium of the system defined in the (figure XX) is between the incremental transversal shear forces and the vertical load p_z (26).

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + p_z = 0 \tag{26}$$

Substituting the equations (24) and (25) in the equation (26) the vertical equilibrium becomes:

$$\frac{\partial^2 m_{xx}}{\partial x^2} + \frac{\partial^2 m_{yy}}{\partial y^2} + 2\frac{\partial^2 m_{xy}}{\partial x \partial y} p_z = 0 \tag{27}$$

By considering the three effects of curvature, twist and bending defined by the equations (19), (20), (22) and (26) the final equilibrium relations are the follows:

$$\begin{bmatrix} -\frac{\partial}{\partial x} & 0 & -\frac{\partial}{\partial y} & 0 & 0 & 0 \\ 0 & -\frac{\partial}{\partial y} & -\frac{\partial}{\partial x} & 0 & 0 & 0 \\ -k_x & -k_y & -2k_{xy} & -\frac{\partial^2}{\partial x^2} & -\frac{\partial^2}{\partial y^2} & -2\frac{\partial^2}{\partial x \partial y} \end{bmatrix} \begin{bmatrix} n_{xx} \\ n_{yy} \\ n_{xy} \\ m_{xx} \\ m_{yy} \\ m_{xy} \end{bmatrix} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \tag{28}$$

2.5 Differential Equation

The differential equation is determined in the following only in regarding to the vertical displacement u_z. As mentioned previously the behavior of shallow shells is coupled between in-plane and out of plane, but the coupled solution is obtained by solving separately the membrane and bending state and coupling them through the differential and Laplacian operators.

2.5.1 In-Plane State

The force method is used to obtain the membrane solution. First, the equilibrium equations are solved by introducing the Airy function Φ. A direct solution of the equilibrium equations may be tried, but in most cases is advantageous to introduce an auxiliary variable, which reduces the system to one second-order equation. The method of the stress Airy function has proved to be a powerful tool for the treatment of this problem and is applied in this case as well (Flügge, 2013). Subsequently the solution of the equilibrium equations the kinematic equations are used. From this last step a compatibility equation between strains and curvatures is obtained and that means that those variables can not change in a free way but they have to satisfy that equation.

By the introduction of the Airy function the membrane forces are the following:

$$n_{xx} = \frac{\partial^2 \Phi}{\partial y^2} - \int p_x dx$$

$$n_{yy} = \frac{\partial^2 \Phi}{\partial x^2} - \int p_y dy \qquad (29)$$

$$n_{xy} = -\frac{\partial^2 \Phi}{\partial y \partial x}$$

Through the membrane forces defined in the equations (29), the third equilibrium equation yields a differential equation for Φ. Considering the geometry of hyperbolic paraboliod shell (Figure 2.12 as the Nakashima Arts Building) and the in-plane loads as zero (px=0 and py=0) the general solution of this differential equation is:

$$\Phi = \frac{1}{2} a p_z xy + f_1(x) + f_2(y) \qquad (30)$$

The solutions of the membrane forces are:

$$n_{xx} = \frac{\partial^2 \Phi}{\partial y^2} = \sqrt{\frac{a^2+y^2}{a^2+x^2}} \frac{d^2 f_2}{dy^2}; \quad n_{yy} = \frac{\partial^2 \Phi}{\partial x^2} = \sqrt{\frac{a^2+x^2}{a^2+y^2}} \frac{d^2 f_1}{dx^2}; \quad n_{xy} = -\frac{\partial^2 \Phi}{\partial y \partial x} = -\frac{a p_z}{2} \qquad (31)$$

In this case the equilibrium solution is very simple as the shear stress is constant along all the shell and the normal forces are constant the straight lines that generates the shell surface (x=const or y=const.). From this follows that the values of the normal forces can be arbitrary prescribed by the way how the edge beams are designed. In case of edge beams with a axial stiffness (*EA*) much higher than the flexural (*EI*) and torsional stiffness the normal forces n_{xx} and n_{yy} in the shell will be approximately zero or much lower than the shear stress as the edge beams are not able to support flexural or torsional forces.

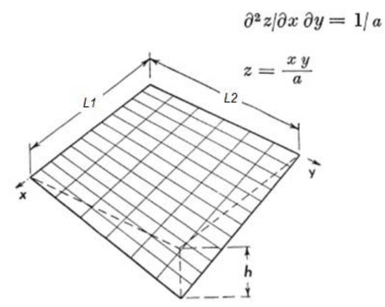


Figure 2.12 - Hyperbolic paraboloid surface
(Flügge, 2013)

By differentiating twice the kinematic equations, regarding the strains $\mathcal{E}_{xx}$, $\mathcal{E}_{yy}$ and γ_{xy} (15), and making the sum, the compatibility equation is reached (32).

$$\frac{\partial^2 \mathcal{E}_{xx}}{\partial y^2} - \frac{\partial^2 \gamma_{xy}}{\partial x \partial y} + \frac{\partial^2 \mathcal{E}_{yy}}{\partial x^2} = k_y K_{xx} - k_{xy} K_{xy} + k_x K_{yy} \tag{32}$$

The constitutive equations the equilibrium solution and the compatibility equations lead to the fourth-order in-plane differential equation (33).

$$\frac{\partial^4 \Phi}{\partial x^4} + 2\frac{\partial^4 \Phi}{\partial x^2 \partial y^2} + \frac{\partial^4 \Phi}{\partial y^4} + D_m(1-v^2)\left(k_x \frac{\partial^2 u_z}{\partial y^2} - 2k_{xy}\frac{\partial^2 u_z}{\partial x \partial y} + k_y \frac{\partial^2 u_z}{\partial x^2}\right) = p_z \tag{33}$$

2.5.2 Out-of-Plane State

The out-of-plane behavior is determined by applying the stiffness method. In this method the derivation starts through the kinematic equations and the last step is the introduction of these equations in the third equation of equilibrium, obtaining so the final differential equation. The bending solution represents the homogeneous solution while the inhomogeneous solution, or the response to the vertical load is represented from the membrane solution which is solved through the force method. For this reason the differential equation of the out-of-plane behavior is determined by excluding the contribution of the load p_z.

Substituting the last three kinematic (15) and constitutive (16) equations in the third equilibrium equation (28), which involves the bending stresses, the fourth-order differential equation is obtained.

$$-k_x \frac{\partial^2 \Phi}{\partial y^2} + 2k_{xy}\frac{\partial^2 \Phi}{\partial x \partial y} - k_y \frac{\partial^4 \Phi}{\partial y^4} + D_b\left(\frac{\partial^4 u_z}{\partial x^4} + 2\frac{\partial^4 u_z}{\partial x^2 \partial y^2} + \frac{\partial^4 u_z}{\partial y^4}\right) = 0 \tag{34}$$

2.5.3 Coupled States

The two differential equations (33) and (34) determined in the chapters above are coupled for the two unknowns Φ and u_z. Coupling the states means to replace those two differential equations by a single one for the unknown u_z. This is done by introducing two operators, Γ differential operator and the Laplacian operator Δ.

$$\Gamma = k_x \frac{\partial^2}{\partial y^2} - 2k_{xy} \frac{\partial^2}{\partial x \partial y} + k_y \frac{\partial^2}{\partial x^2}$$

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \tag{35}$$

Through this two operators the equations (33) and (34) become:

$$\Delta\Delta\Phi + D_m(1 - v^2)\Gamma u_z = p_z \tag{36}$$

$$-\Gamma\Phi + D_b \Delta\Delta u_z = 0 \tag{37}$$

Considering shells of constant curvatures k_x, k_y and k_{xy} is possible to write that ΔΓ=ΓΔ. The final eight order differential equation is obtained by applying once the operator Γ to the equation (36) , and twice the operator Δ to the equation (37) and subsequently by eliminating the Airy stress function.

$$D_b \Delta\Delta\Delta\Delta u_z + D_m(1 - v^2)\Gamma^2 u_z = \Delta\Delta p_z \tag{38}$$

The solution of the eight-order differential equation has to be found through 16 boundary conditions, four at every edge. At every edge two boundary condition concern the membrane state and other two the bending behavior. The membrane boundary conditions are regarding the in-plane displacements or membrane forces n_{xx}, n_{xy}. The boundaries concerning the out-of-plane behavior affects the as called edge disturbance of the shell. Depending on the bending boundaries the edge disturbance or the intensity and distribution of the moments will be higher or lower. The figures below show different bending boundary conditions. The second boundary of the free edge is obtained through the *Kirchhoff theory for thin plates*.

$\frac{\partial \mathrm{u_t}}{\partial \mathrm{n}} = 0 \quad \mathrm{u_t} = 0$

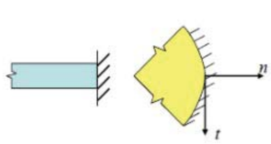


Figure 2.13 - Clamped Edge

$\mathrm{m_n} = 0 \quad \mathrm{u_t} = 0$

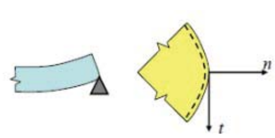


Figure 2.14 - Hinged Edge

$\mathrm{m_n} = 0 \quad \frac{\partial \mathrm{m_{nt}}}{\partial \mathrm{t}} + \mathrm{v_n} = 0$

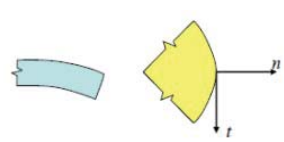


Figure 2.15 - Free Edge

(Petr Kabele, SAHC lectures, 2016)

All these considerations on the theory of shallow shells are applied in the Analytical Solution of the Nakashima Arts Building where the geometry and boundary conditions are taken into account properly, in order to describe in the best way possible the real structural configuration.

3. ANALYTICAL SOLUTION OF HYPERBOLIC PARABOLOID SHELLS

Solving directly the eight order partial differential equation (39) coming out from considering the coupled states, in plane and out of plane behavior, for one displacement can result extremely complicated and time consuming. The problem is solved by considering separately the membrane solution and the out of plane solution or bending solution. As mentioned in the Chapter 2 (Theory of Shallow Shells – Donnell Theory) the membrane solution is obtained from the force method, instead the out of plane solution is obtained from the stiffness method.

$$D_b \cdot \Delta\Delta\Delta\Delta u_z + D_m \cdot \Gamma^2 = \Delta\Delta P_z \tag{39}$$

3.1 Membrane Solution for Uniform Load

The membrane solution starts from solving the equilibrium equations by the introduction of the Airy stress function Φ (3).

$$n_{xx} = \frac{\partial^2 \Phi}{\partial y^2} - \int p_x dx\ ;\ n_{xx} = \frac{\partial^2 \Phi}{\partial y^2} - \int p_x dx;\ n_{xy} = -\frac{\partial^2 \Phi}{\partial y \partial x} \tag{40}$$

As explained in the Chapter 2 (Theory of Shallow Shells – Donnell Theory) above the third equilibrium equation and the airy function yield to a differential equation which, in case of Px and Py equal to zero and for a hyperbolic paraboloid shell surface has as a general solution the equation (41) from which is possible to obtained the equations for n_{xx}, n_{yy} and the shear n_{xy} (42).

$$\Phi = \frac{1}{2} a p_z xy + f_1(x) + f_2(y) \tag{41}$$

$$n_{xx} = \sqrt{\frac{a^2+y^2}{a^2+x^2}}\ \frac{d^2 f_2}{dy^2}\ ;\ n_{yy} = \sqrt{\frac{a^2+x^2}{a^2+y^2}}\ \frac{d^2 f_1}{dx^2}\ ;\ n_{xy} = -\frac{1}{2} a p_z \tag{42}$$

The solution shows that the shear stress is constant throughout the shell and the normal stresses are each constant along those straight lines that generates the shell surface (x=const. or y=const) and may vary only from one such straight line to the other. Assuming that the edge boundaries of the structure are not able to support normal stresses n_{xx} and n_{yy} coming from the shell, which means that they have zero flexural and torsion rigidity, the final solution represented by the following equations (43).

$$n_{xx} = 0\ ;\ n_{xx} = 0;\ n_{xy} = -\frac{1}{2}\ a p_z \tag{43}$$

Combining the solution with the constitutive equations is possible to determine the normal and shear strains (44). The normal strains are zero and the shear strain is constant.

$$\varepsilon_{xx} + v\varepsilon_{yy} = 0$$

$$\varepsilon_{yy} + v\varepsilon_{xx} = 0 \tag{44}$$

$$\gamma_{xy} = \frac{2n_{xy}}{2D_m(1-v)} = -\frac{1}{D_m(1-v)}ap_z$$

The displacements are obtained through the kinematic equations using the strains obtained from the constitutive equations (44). The displacement expression are the following:

$$\frac{\partial \mathrm{u_x}}{\partial x} = 0$$

$$\frac{\partial \mathrm{u_y}}{\partial y} = 0 \tag{45}$$

$$\gamma_{xy} = \frac{\partial \mathrm{u_x}}{\partial y} + \frac{\partial \mathrm{u_y}}{\partial x} - 2k_{xy}u_z = -\frac{2}{a}u_z$$

From the first two equations is possible to deduce that the tangential displacements are constant and for hyper structures supported at angular points these displacements must be zero. The vertical displacement is obtained by combining together the third equations of (44) and (45).

$$\mathrm{u_x} = 0$$

$$u_y = 0 \tag{46}$$

$$u_z = \frac{1}{2D_m(1-v)}\ a^2p_z$$

The membrane solution obtained is considered to be the inhomogeneous solution of the eight order partial differential equation (39). Summing up the membrane solution includes three important assumptions that make the response of the shallow shell rather simple. The first simplification considers the own self weight of the structure acting as normal to the surface. This assumption can be taken only when the elevation is small compared with the span. The second assumption is related to the first and the in-plane load is considered to be zero and the normal load is uniformly distributed over the shell surface. The third assumption involves the edges and they are considered to be infinitely stiff in the axial direction and zero flexural and torsion rigidities.

3.2 Bending Solution

The out of plane solution is considered as the homogeneous solution of the differential equation (39) and represents the edge disturbance needed to compensate the shortcomings (in terms of stresses) of the membrane response at the boundaries. The exact solution of the homogeneous differential equation is difficult to obtain and not suitable for application in structural design. In this case an approximate solution has been considered according to (Blaauwendraad and Hoefakker, 2014).

The approximation is due to two considerations. The edge load or edge displacement, which is necessary to compensate the shortcomings of the membrane solution, is described by a smooth function in the direction of the straight edge. The second assumption is that for such an edge load the stress resultant and the displacement vary rapidly in the direction normal to the straight edge. Because of the two assumption mentioned above, for an edge normal to X-direction with length Ly, the derivatives respect to Y are negligibly small compared to those with respect to X and only the highest derivative with respect X has to be retained and the differential equation (3 becomes the equation (47). This assumptions involve only the bending behavior and in the differential equation (39) they can be made only in the part that describes the bending action which is Δ, instead the operator Γ describes the membrane action so this last term should not be neglected or adapted.

$$D_b \frac{\partial^8 u_z}{\partial x^8} + \frac{4D_m(1-v^2)}{a^2} \frac{\partial^4 u_z}{\partial x^2 \partial y^2} = 0 \tag{47}$$

The reduced differential equation is obtained by integrating twice with respect X and dividing by D_b:

$$\frac{\partial^6 u_z}{\partial x^6} + \frac{4D_m(1-v^2)}{D_b a^2} \frac{\partial^2 u_z}{\partial y^2} = 0 \tag{48}$$

By introducing the parameters λ and α_n the reduced equation becomes:

$$\lambda^4 = \frac{4D_m(1-v^2)}{D_b a^2} = \frac{48(1-v^2)}{(at)^2}; \alpha_n = \frac{n\pi}{L} \tag{49}$$

$$\frac{\partial^6 u_z}{\partial x^6} + \lambda^4 \frac{\partial^2 u_z}{\partial y^2} = 0 \tag{50}$$

The trial solution for an edge with X- constant is represent by the equation (51) where α=π/L, r are the roots to be determined and A is a constant which depends on the boundary conditions.

$$u_z(x; y) = Ae^{rx} \cos{(\alpha y)} \tag{51}$$

The equation (52) is the result of substituting the trial solution in the reduced differential equation and is characterized by six roots (54). The additional parameter β (53) is introduced.

$$r^6 - \lambda^4 \alpha^2 = 0 \tag{52}$$

$$\beta = \sqrt[6]{r} = \sqrt[r]{\lambda^4 \alpha^2} = \frac{\sqrt[6]{48\pi^2(1-\nu^2)}}{\sqrt[3]{(a+l)}} \tag{53}$$

$$r_{1,4} = \pm\beta;\ r_{2,5} = \pm\frac{1}{2}\beta(1+i\sqrt{3});\ r_{3,6} = \pm\frac{1}{2}\beta(-1+i\sqrt{3}) \tag{54}$$

The u_z function is composed by two parts, one that decays for an X- coordinate that starts at the edge and one that increases. This means that is equivalent to a solution part that decays from the considered edge and one that decays from the opposite edge. It is assumed that the edges are far enough to avoid superposition of effects so both decaying parts have vanished at the opposite edge (Figure 3.1) so only the negative roots are considered (55).

$$\begin{aligned} r_1 &= -\beta \\ r_2 &= -\frac{1}{2}\beta(1+i\sqrt{3}) \\ r_3 &= -\frac{1}{2}\beta(-1+i\sqrt{3}) \end{aligned} \tag{55}$$

Figure 3.1 – Assumption about the edge disturbance

From the three roots the final solution in terms of u_z is obtained (56), and the values of the constants A_1, A_2 and A_3 depend on the boundary conditions at the edge.

$$u_z = \left\{A_1 e^{-\beta x} + \mathrm{e}^{-\frac{1}{2}\beta x}\left(A_2 \mathrm{e}^{\frac{1}{2}\beta i\sqrt{3}x} + A_3 \mathrm{e}^{-\frac{1}{2}\beta i\sqrt{3}x}\right)\right\} \cos(\alpha y) \tag{56}$$

Through this differential equation and the boundary conditions the moments, shear forces or membrane forces can be computed, but as an edge disturbance the most relevant plot is the one regarding the moments. This is due to the fact that the normal stresses close to the edges are reflected by bending moments that will create the so called *edge disturbance*. Before presenting the solution in terms of moments is convenient to define the meaning of the influence length l_i. The influence length represents the distance between the roots of the differential equation defined above. In other words l_i is the distance from a zero value to a zero value and at a distance larger than l_i the edges disturbance can be considered as finished. As the differential equations are solved in according to the geometry of the structure, the influence length will also vary depending on the structure geometry the Figure 3.2 shows the influence length in different type of geometries.

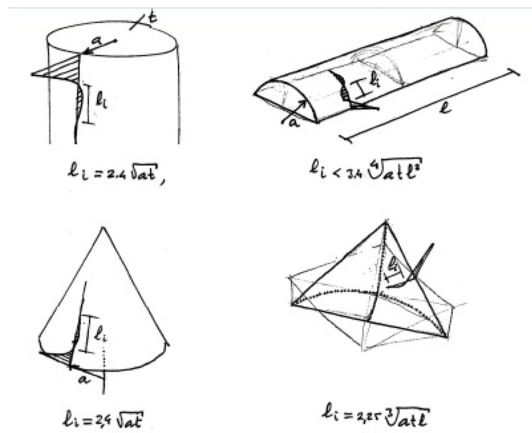


Figure 3.2- Influence length in different structures

The influence length is also defined as the ration *2π/β* and in the case of an hyperbolic paraboloid structure it is almost equal to $2.25\sqrt[3]{atl}$. Often in literature the characteristic length is used too and is defined as $l_c = \sqrt[3]{atl}$. The influence length can also be used for the determination of the mesh density in a numerical model in order to have a good accuracy of the edge disturbance in term of moments.
Concerning the solution of the differential equation in terms of moments, Loof(Loof, 1961) has developed simplified formulas, according to the theory explained in this report, for bending disturbance of hyppar roofs under uniform load p_z. The solution is provided for two types of boundary conditions, clamped and hinged edges, and it has been used for the verification of the numerical model. The following formulas are regarding and edge oriented in the Y-direction and show the values of the moment mxx and shear vx in the corresponding distance X.
For clamped edge:

$$
\begin{gathered}
m_{xx} = 0.511\xi^4 p_z l^2 \qquad v_x = 1.732\xi p_z l \qquad x = 0 \\
m_{xx} = -0.617\xi^4 p_z l^2 \qquad x = 0.85\, l_c
\end{gathered}
\tag{57}
$$

For hinged edge:

$$
\begin{gathered}
v_x = 0.577\xi p_z l \qquad x = 0 \\
m_{xx} = -0.149\xi^4 p_z l^2 \qquad x = 0.55\, l_c
\end{gathered}
\tag{58}
$$

where:

- $\xi = \frac{l_c}{l}$

Figure 3.3 and Figure 3.4 show the distribution of the moments, for the two different boundary conditions considered, in the direction perpendicular to the edge.

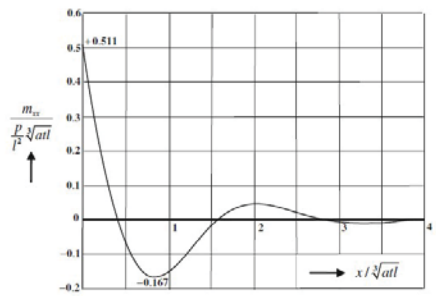


Figure 3.3 - m_{xx} distribution in clamped edge (Loof, 1961)

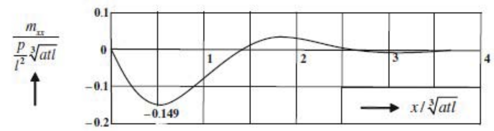


Figure 3.4 - m_{xx} distribution in hinged edge (Loof, 1961)

3.3 Analytical Solution for the Nakashima Arts Building Roof

Based on the theory of shallow shells and on the approximate solution explained in the chapters above the analytical solution, regarding the roof of Nakashima Arts Building, was performed. The geometrical parameters are summarized in the Table 3.1. It is important to underline that in this analytical solution the parameter $k_{xy}=1/a$ is indicated as c, and with a is indicated the length of the horizontal edge beam as in the Figure 3.5.

Table 3.1- Geometrical parameters

Geometrical parameters	[m]
a	10,668
b	10,668
h	4,2672
c	26,67
l	11,49
t (thickness)	0,054

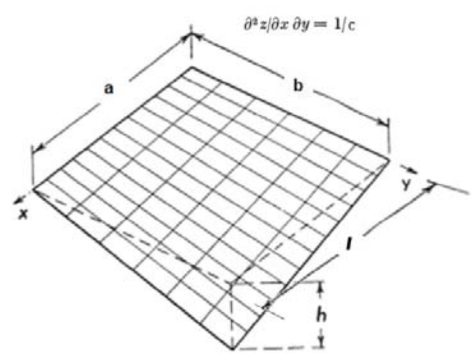


Figure 3.5 - Annotation of the geometrical parameters (Flügge, 2013)

The load applied is the same as the simplified solution and it has been determined considering the weight of the plywood layers, covering material, ribs and a uniform distribution of the snow (Table 3.2). The solution is in accordance with the approximate solution, and considers that the in-plane loads (px and py) as zero and that the normal stresses n_{xx} and n_{yy} are zero far from the edges that are affected by the boundary conditions (a and b). This assumption has been made because the tilted edge beams are considered to have zero bending and torsional stiffness as their cross sections goes decreasing from the support to the free edge.

Close to the horizontal edges (a and b) the bending behavior is more relevant and its has to be referred to this areas.

The determination of the moments m_{xx} or m_{yy} due to the edge disturbance has been provided for two type of boundary conditions, clamped and hinged. Since the structure, boundary conditions and the load are symmetric the bending solution for the edge *a* will be the same as for the edge *b*.

One of the most important assumptions of the bending behavior is that the edges are far enough to avoid superposition of effects but in the case of Nakashima Arts Building this assumption is not valid as the two edge beams a and b share a corner (Figure 3.6). In this report this effect has not been taken into account and the distribution of the moments along the edges is considered to constant or with low variation. This problem of superposition of effects in the shared corner can be taken into account by the finite element modeling.

In the following Table **3.4** and Table 3.5 the solutions obtained, respectively for membrane and bending behavior (for two type of boundary conditions), are shown and the critical length l_c, influence length l_i and the ξ parameter for the horizontal edge beams, a and b, are the following:

Table 3.2 - Load definition

Load Type	[kN/m²]	
Plywood (3layers)	0,287	
Ribs	0,024	
Celotex (2 layers)	0,024	
Aspfalt felts	0,096	
Marble chips	0,718	
Snow load	1,436	30 psf
TOT	**2,585**	54 psf

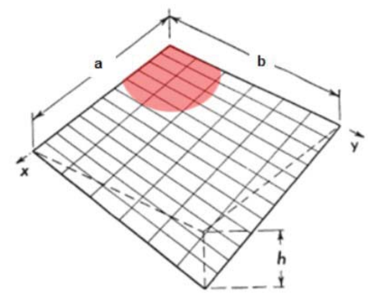


Figure 3.6 – Corner affected by superposition of effects

$$\xi = \frac{l_c}{l} = 0.22$$

$$l_c = \sqrt[3]{atl} = 2.49\ [\mathrm{m}] \qquad (59)$$

$$l_i = 2.25\sqrt[3]{atl} = 5.60\ [m]$$

The mechanical parameters used for the determination of the solution are summarized in the Table 3.3:

Table 3.3 - Mechanical properties

E	7500000	[kPa]
v	0	
$D_m = \frac{Et}{(1-v^2)}$	405000	[kN/m]
$D_b = \frac{Et^3}{12(1-v^2)}$	98,415	[kN/m]

Table 3.4 - Membrane solution

$n_{xy} = \frac{cp_z}{2}$	34,47	[kN/m]
$\sigma_{xy} = \frac{n_{xy}}{t}$	638,35	[kN/m^2]
$u_z = \frac{c^2 p_z}{2D_m(1-\nu)}$	0,002270	[m]
γ_{xy} = -c*pz/(Dm*(1-v))	-0,0001702	[-]

Table 3.5 - Bending solution

Clamped Edge				
Y=0		$m_{xx} = 0{,}511\xi^4 p_z l^2$	0,329	[kN*m/m]
		$v_x = 1{,}732\xi p_z l$	10,593	[kN/m]
Y=0,85*lc	2,1131	$m_{xx} = -0{,}167\xi^4 p_z l^2$	-0,108	[kN*m/m]
Hinged Edge				
Y=0		$v_x = 0{,}577\xi p_z l$	3,4427	[kN/m]
Y=0,55*lc	1,3673	$m_{xx} = -0{,}149\xi^4 p_z l^2$	-0,09606	[kN*m/m]

The Figure 3.7 shows the distribution of the moments in the edge disturbance for the two different boundary conditions, clamped and hinged edge. It can be noticed that the effect of the edge disturbance is negligible at a distance of around 6 meters from the edge and this is in accordance with the influence length determined above that is 5.60 meters.

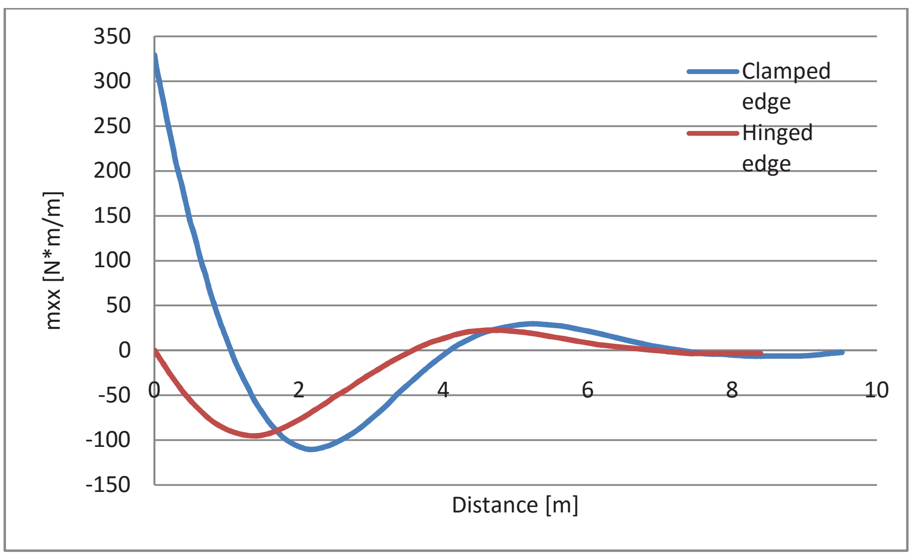


Figure 3.7– Moments distribution

4. SIMPLIFIED DESIGN METHOD

Due to the complex understanding of the behavior of hyper shell structures and its complex designing process simplified rules for the determination of the stresses have been developed. The reference used for the understanding of this simplified rules is (West Coast Lumbermen's Association, 1964). This reference was useful not only for the understanding of the simplified design process used but also for the construction process which is strongly related with the stress distribution in a structure. The structure analyzed is an hyperbolic-paraboloid shell of lumber. The article refers specifically to the forest production pavilion designed by the architect John Storrs and designed by the structural engineer James G. Pierson (Figure 4.1).

Figure 4.1- Forest Productions Pavilion - John Storrs (West Coast Lumbermen's Association, 1964)

The construction process is composed by different steps and it start at first with the placing of the edge beams of the hyperbolic-paraboliods in order to create the skeletal frame (Figure 4.2). When the skeleton is completed the following step is the introduction of the temporary purlins which will allow the application of the double layer diaphragm. The double diaphragm is composed by two layers oriented in opposite direction and glued together. The connection between the boards is tongue and groove and over the edge stiffener the layers are glued and helix nailed. The weakest parts of the shells structure are the edges and is needed to ensure a proper connection between the edge beams and the shell's layers and that is why the edge beams are thickened by adding more boards nailed and glued around the perimeter. The structure is completed by making thicker the edge beams removing the temporary purlins. The figures below shows briefly the building steps followed in this case.

Figure 4.2* - 1st: Placing the edge beams

Figure 4.3* - 2nd: Placing the purlins

Figure 4.4* - 3rd: Application of the double layer shell

Figure 4.5* - 4th: Edge beams thickened

Figure 4.6* - 5th: Removing of the temporary purlins

*Pictures reference: (West Coast Lumbermen's Association, 1964)

The structural analysis starts from the assumption that the dead load for this kind of structures as is very small compared to the live load and the non-uniform distribution of it is neglected. The forces considered and computed are the reactions, the compression in the perimeter members, the shear forces at the junction of the sheathing and the perimeter members, and the tensile and compression forces in the sheathing. These forces are solved by simple proportions rules.

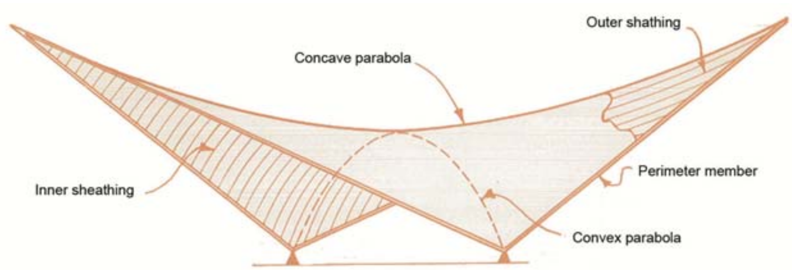


Figure 4.7 - Hyperbolic-Parabolid Shell (West Coast Lumbermen's Association, 1964)

The following Figure 4.8 is an isometric view of the hyperbolic-parabolid shell where all the where:

- a length of one side
- a' length of the horizontal projection of a
- h vertical distance from a support to the highest point of the shell
- k Inclined distance from a support to the midpoint of the length l
- l_1 length along longitudinal axis
- l_2 length along transversal axis
- H horizontal thrust
- R vertical reaction
- F resultant of the vertical reaction R and the horizontal thrust H
- C total compression force in perimeter member
- c principal compressive force in sheathing per meter
- t principal tension force in the sheathing per meter
- v boundary shear force per meter

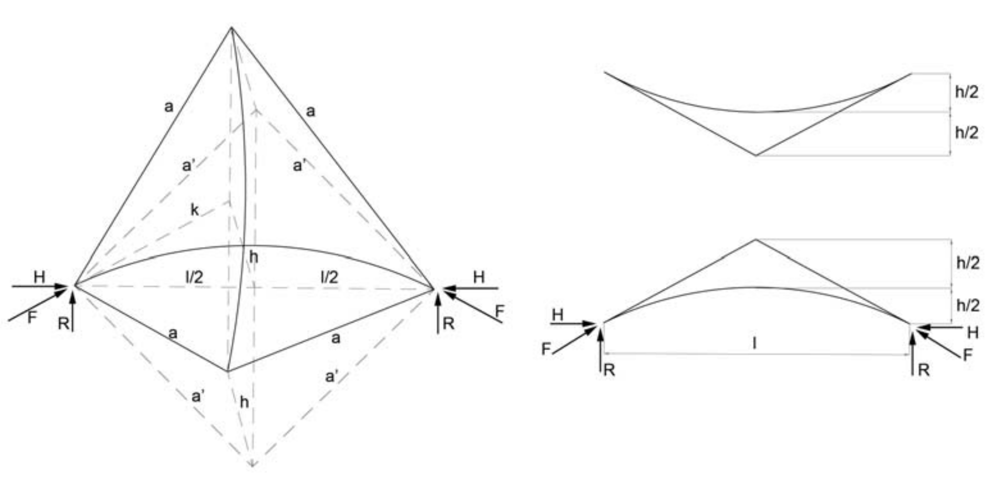


Figure 4.8 - Isometric view of the shell

Reaction Forces and Compression in the Edge members

Each of the vertical reactions for balanced live and dead loads are quiet easy to compute and consist on one-half the sum of the vertical loads. The horizontal thrust, H, and the force F are calculated by the following proportions:

$$\frac{R}{h} = \frac{H}{l/2} \text{-->} H = \frac{Rl}{2h} \qquad \frac{F}{k} = \frac{R}{h} \text{-->} F = \frac{Rk}{h} \tag{60}$$

The compressive force in the edge members is determined as the component parallel to the perimeter members of the force F.

$$\frac{F/2}{k} = \frac{C}{a} \text{-->} C = \frac{aF/2}{k} \tag{61}$$

Stress in Sheathing and Boundary Shear

One of the assumption in the determination of the stress distribution in the shell is that the structure is working in pure shear so the principal forces are tensile forces, t, parallel to the direction of the concave parabolas; and compressive forces, c, parallel to the direction of the convex parabolas (Figure 4.9). This assumption leads to a shearing force acting along the length of the perimeter members at the junction of the sheathing and the perimeter members. This boundary shear, v, will be transferred to the perimeter members as a compression force. This assumption is respected if the flexural and torsional rigidity are much lower than the axial rigidity which for this type of structures is common. Referring to the Figure 4.9 the principal forces are:

$$\frac{t}{v} = \frac{l_1/2}{a\prime} \text{-->} t = \frac{l_1 v}{2a\prime}; \qquad \frac{c}{v} = \frac{l_2/2}{a\prime} \text{-->} c = \frac{l_2 v}{2a\prime}; \qquad v = \frac{C}{a} \tag{62}$$

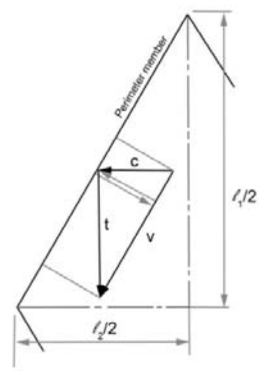


Figure 4.9 - Stress in Sheathing

If the projection of the hyperbolic-paraboloid structure is a square, the principal tension and compression forces will be equal in magnitude. The unit tensile and compressive stresses are equal to the principal forces, t and c, divided by the thickness of the shell.

As mentioned above the construction process affects the distribution of the internal forces in the structure, indeed if the sheathing is placed in the direction parallel to the longitudinal and transverse axes, each layer acts independently, one is taking the compression and one the tension. In this case nailing or stapling between the layers is not needed for strength but just for preventing the buckling of the compression layer and for increasing the stiffness of the shell.

When the layers are placed with the boards parallel to the sides, each layer is resisting to a portion of the principal compression force and to a portion of the principal tension force. This behavior result in a shear between the two layers and the resistance to this shear is given by the type of fastening between the two layers.

For a better understanding and verification of the simplified rules, a numerical example was solved by both the simplified method and the finite element (FE) method. The dimensions of the structure were adopted from those of the Nakashima Arts Building. It should be noted, however, that the simplified rules are derived for a leveled hyppar (with opposite apexes at the same height, Figure 4.7), while the roof of Nakashima Arts Building is inclined (Figure 1.8). Therefore, first a leveled shell is considered, to be consistent with the assumptions of the simplified model. Secondly, an inclined shell is analyzed to verify, whether the simplified method can be used for this case as well.

The first leveled structure with dimensions adopted from the Nakashima Arts Building is obtained by rotating it around the axis AB as shown in the Figure 4.10. The edges of this roof are not equal (the two horizontal are 10.668 [m] instead the other two inclined 11.49 [m]) but in order to be able to apply the simplified formulas this difference is neglected and the edges are considered all the same with a length of 11.49 [m]. The Table 4.1 summarizes the geometrical properties of the analyzed structure.

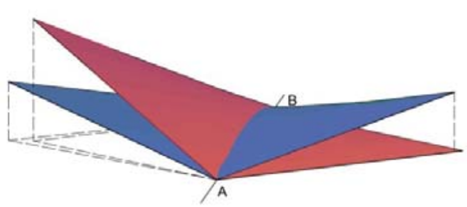


Figure 4.10 - Rotation axis of the Nakashima Arts Building roof

Table 4.1- Geometrical properties of the first leveled structure

a	11,49	[m]
a'	11,30	[m]
h	2,05	[m]
k	8,25	[m]
l	15,98	[m]
Shell Area	129,08	[m^2]
Shell thickness b	0,05	[m]

The load applied in the structure includes the plywood, covering materials, ribs and the snow load. The Table 4.2 shows their intensities and the total load.

Table 4.2 - Loads definition

Load Type	**[kN/m^2]**
Plywood (3layers)	0,287
Ribs	0,024
Celotex (2 layers)	0,024
Aspfalt felts	0,096
Marble chips	0,718
Snow	1,436
Tot	**2,585**

By defining the geometrical dimensions the simplified analysis explained above was computed and the results in terms of reaction and stresses in the edge members and in the shell are shown in the Table 4.3.

Table 4.3 - Results obtained from the simplified solution

R	166,84	[kN]
H	649,32	[kN]
F	670,41	[kN]
C	466,86	[kN]
v	40,63	[kN/m]
t	28,73	[kN/m]
c	28,73	[kN/m]
P. stress – t	574,62	[kN/m^2]
P. stress - c	574,62	[kN/m^2]

The result in terms of stresses are in the principal direction and as one of the assumption was that the shell is working just in pure shear the shear stress XY is obtained by multiplying the principal stress by the root of two.

$$\vartheta_{XY} = t * \sqrt{2} = 812.63\ [kN/m^2] \tag{63}$$

5. FEM CONCEPT

The structural analysis of shells is characterized by difficult and complex governing equation to solve. This, in the seventies, was reflected directly in the process of deign where engineers had to put considerable effort to verify their designs in accordance to the rigorous methods. Many approximate methods were developed. Cylindrical shell for example was approached as beam when extended in the long direction, while was considered as an arch when was shortened in the same direction (Bradshaw et al., 2002). Another famous method, adopted also by famous architects as Antoni Gaudi in the Sagrada Familia, was to obtain the funicular shape of the shell by hanging weights from a mesh.

The development of the finite element helped on the understanding of the structural behavior of these structures and it also made the design process more simple. The concept of the finite element method is to describe the structure by a certain number of elements which are “reassembled” using the equilibrium and compatibility equations (Bradshaw et al., 2002). In each element, the displacement is approximated by a function of suitable type as for example linear or quadratic. From this approximation of the displacements are calculated the kinematic and constitutive equations. In FE method the relation generalized stresses-external forces is not obtained through the equilibrium equations but through principle of virtual work or of total potential energy. Through this steps the discretized weak form for every element is obtained (64). In this equation K is the stiffness matrix, d vector of nodal degrees of freedom and f_{ext} is the external force vector.

$$K_e d_e = f_{ext} \qquad (64)$$

The most suitable elements used for modeling shell structures are triangular or quadrilateral plane elements. In the case of hyperbolic paraboloid shell obtained as a ruled surface the quadrilateral elements are the most suitable.

In this thesis the structure is modeled using the ADINA (Automatic Dynamic Incremental Nonlinear Analysis). The elements used to describe the structural parts of the building are listed in the following:

- *4- Node isoparametric shell elements:* these elements are used to describe the plywood shell structure. The shell element is formulated treating the shell as a three-dimensional continuum with the assumptions used in the Timoshenko beam theory and the Reissner/Mindlin plate theory (ADINA R&D, 2016). At every shell element midsurface node are assigned 5 degree of freedom in according to the recommendations given by the ADINA manual. The 4-node element has been chosen because “it does not lock and has a high predictive capability and hence can be used for effective analysis of thin shells” (ADINA R&D, 2016). The numerical integration used is the Gauss integration and three integrations point through the thickness were adopted, in order to catch the bending behavior (Figure 5.2). The definition of the elements local axis is shown in Figure 5.1.

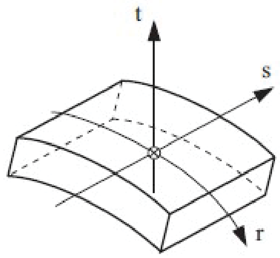


Figure 5.1 - Definition of the local Cartesian System (r, s, t) (ADINA R&D, 2016)

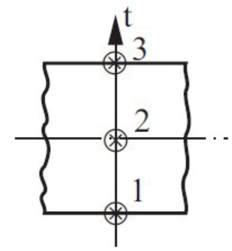


Figure 5.2 - Integration points through the thickness in the Gauss integration (ADINA R&D, 2016)

- *2-Node truss elements:* these elements are used to describe the edge beams in the numerical analysis concerning the verification of the model and the comparison with the simplified designing rules.

  The choice of these elements aims to have the same assumptions between the numerical modeling and the analytical solutions carried out from the theory of thin shells. In the truss element the only force that can be transmitted is the longitudinal force and in the case of 2-node truss, this force is constant. Only one integration point is used (Figure 5.3) and the Gauss numerical integration has been adopted (ADINA R&D, 2016).

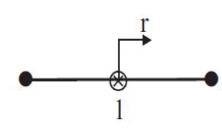


Figure 5.3 - One-point Gauss integration (ADINA R&D, 2016)

- *2-Node Hermitian beam elements:* these elements are used in the analysis concerning the boundaries and load cases effects on the Nakashima Arts Building.

  Through these elements are described the tilted edge beams, since it was needed to take into account the effective cross section properties. The formulation of the beam is a generalization of the Euler-Bernoulli beam formulation (ADINA R&D, 2016). The Figure 5.4 shows the local Cartesian system and the degrees of freedom. In the r direction is used a 5 – integration order.

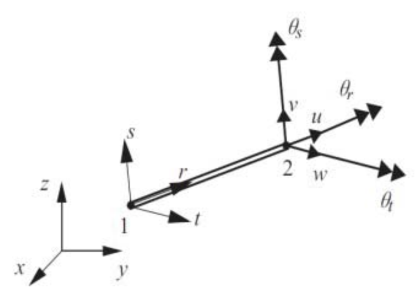


Figure 5.4 - Local Cartesian system and DOF of beam element (ADINA R&D, 2016)

6. VERIFICATION OF THE FE MODELING

With the aim of verifying the FE modeling a comparison between the analytical solution and the FE solution has been done. The numerical model is developed using the software ADINA.

Once the geometry was created the mechanical properties have been assigned. Since the analysis is linear elastic and the material is considered as isotropic, only the Young's modulus defines the mechanical behavior of the material. At this step of the thesis work, a grading of the plywood and edge beams materials was not yet available. Due to this reason the Young's modulus of the plywood was adopted as $E = 7{,}5\ [GPa]$ from the Table 2 of the article "*Effect of weathering on surface quality and structural properties of six species of untreated commercial plywood siding after 6 years of exposure in Alabama"* (Biblis, 2000).

One of the assumption in the simplified solution is that the edge beams are infinitely rigid in the axial direction and zero flexural and torsion rigidity. To take this assumption in account into the FE model the Young's modulus assigned to the edge beams is the one of the shell increased by a magnitude order of three. Moreover as elements that describes the behavior of these edge beams have been used truss elements (Chapter 5 – FEM Concept). Through those measures the edge beams are considered to be infinitely stiff in the axial direction. The plywood shell surface is modeled by 4-node shell elements (Chapter 5 – FEM Concept).

The load, which has the same intensity as in the analytical solution, has been applied in the direction normal to the surface.

Concerning the boundary conditions, two different configurations have been solved. In the first the horizontal edges are fixed in displacements and rotations, instead in the second case they are fixed only in displacements.

The two different configurations are compared with the analytical solution in terms of shear stresses concerning the membrane behavior, and in terms of moment distribution perpendicular to the edge concerning the bending behavior. In order to have a good accuracy of the edge disturbance the mesh has a density of 100x100 elements. The figures below show the two different case of boundary conditions analyzed (Figure 6.2 and Figure 6.3), the mesh density (Figure 6.5) and load applied as normal to the surface (Figure 6.4).

The band plots showed in the following chapters refer to the orientation of the shell as in figure Figure 6.1 (x and y are the global axis).

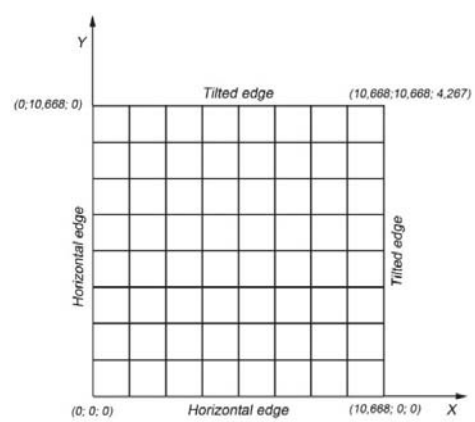


Figure 6.1 - Orientation reference for the band plots

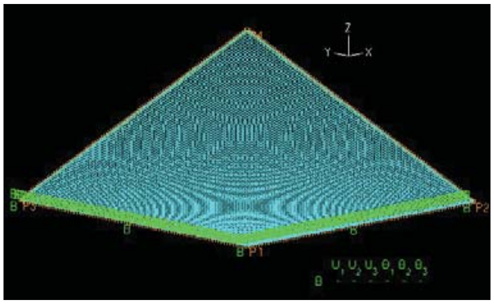


Figure 6.2 - Boundary conditions - Clamped Edges

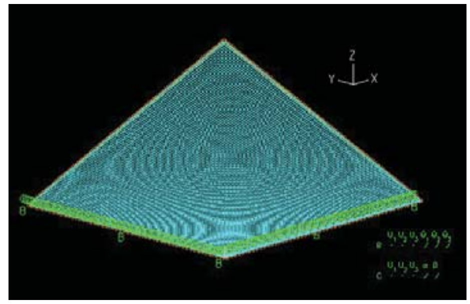


Figure 6.3 –Boundary conditions – Hinged edges

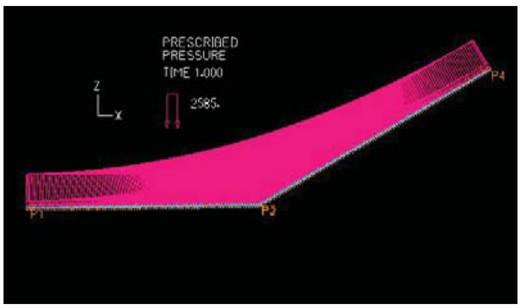


Figure 6.4 - Load normal to the surface

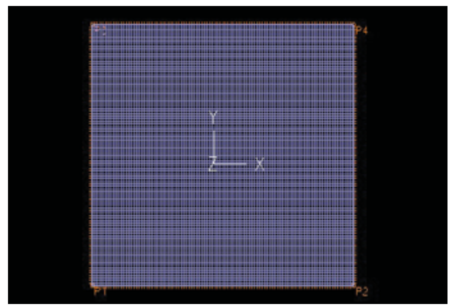


Figure 6.5 - Mesh density

6.1 Clamped Horizontal Edges

The deformation of the structure and the band plot of the vertical displacement (Figure 6.6) underline that apart from the area of the free edges and nearby the horizontal edge, the displacement is around 0.002 [m] (the average in all the structure is 0.00281 [m]) which is the almost the same result as predicted in the membrane solution (u_z=0.00227 [m]).

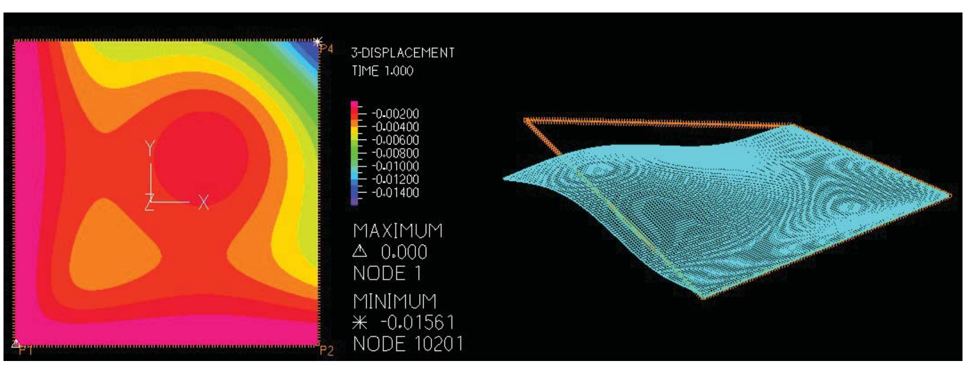


Figure 6.6 - Vertical displacement and structure deformation (magnification factor 150)

Concerning the membrane shear stresses (τ_{rs}), the Figure 6.7 explains clearly the influence of the boundary conditions. Far from the edges the distribution is almost uniform and varies in a range 660 [kPa] and 849 [kPa] (Figure 6.8). Considering a quantitative comparison the average value of the shear stresses in the numerical analysis is 740 [kPa] which differs from the analytical solution (638 [kPa]) by 13%. This difference is acceptable and is due to the fact that the FE model does not impose a-priori any assumption concerning the stress distribution and the stiffness of the edge beams and it provides an approximate numerical result of the original differential equation.

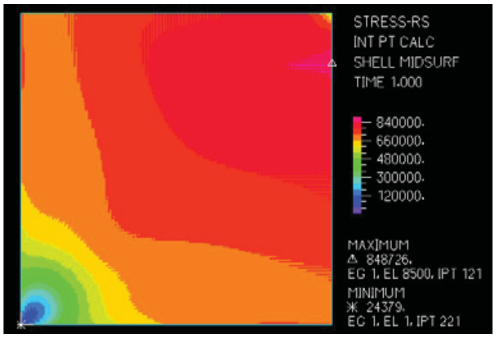


Figure 6.7 – Distribution of shear stresses rs

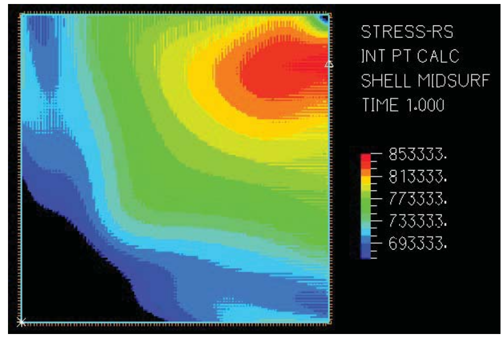


Figure 6.8 – Distribution of shear stresses rs – Range 660/850 [kPa]

The last step of comparison is regarding the bending moment distribution. In the Figure 6.10 is shown the distribution of the bending moment M_{rr} (Figure 6.9), where the axis r, s and t are the local axis of the shell element (Chapter 5 –FEM Concept).

The bending plot underlines immediately that there are two areas where there is a much higher concentration of moments. The first is in the corner A (Figure 6.10) between the two horizontal edges and this is due to the superposition of effects. In this area is also localized the maximum value of the moment.

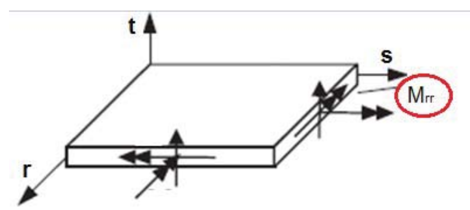


Figure 6.9 – M_{rr} in the shell element

The same thing is happening in the corner B (Figure 6.10) between the two tilted edges. Since these two edges are not affected by boundary conditions and are modeled as trusses the superposition of the effects is much lower than the corner between the horizontal edges.

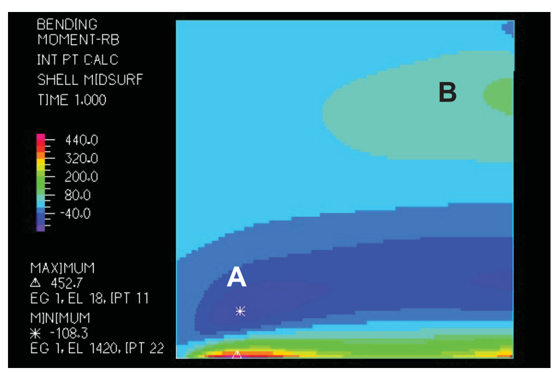


Figure 6.10 – Distribution of moments M_{rr}

The superposition of effects is also reflected in the distribution of moments along the edge beams. In the analytical solution one assumption was that this distribution is a smooth function that for the case that we solved means constant along the edge. The Figure 6.11 shows the distribution of moment M_{rr} along the edge oriented in Y=0 and the constant value obtained from the analytical solution. From the comparison the solution obtained analytically seems to be close to the numerical in the central area of the edge beams. This is due to the fact that the central area is at the maximum distance from the corners and so here the superposition of effects is lower than the other areas.

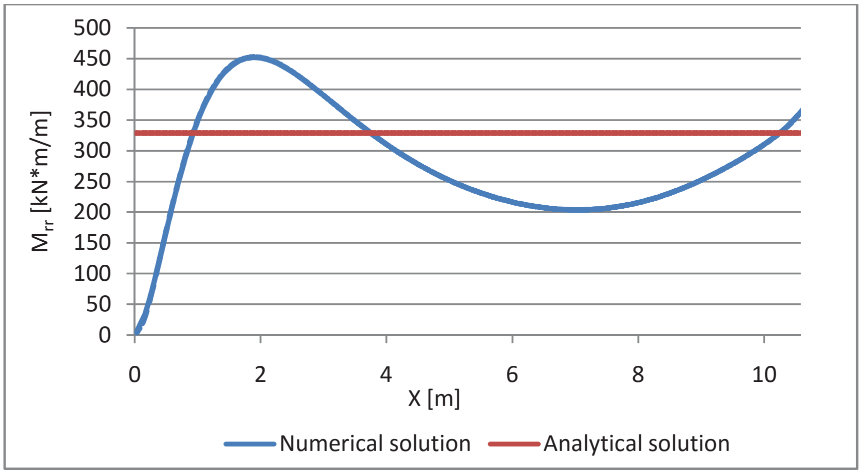


Figure 6.11 - Distribution of moments in the edge Y=0

In order to have a further understanding, have been computed the moments in the direction perpendicular to the horizontal edge Y=0. Three directions have been considered: the first is passing through the maximum and minimum moments close to the corner A; the second is at a distance of almost 5 meter (half of the edge); the last is almost at the end of the edge (X=8 [m]) in order to get the superposition of the effects in the corner B. These three sections (Max, Middle, Min), Figure 6.12, have been plotted in the same graph of the analytical solution (Figure 6.13).

The comparison shows that the more the distance X is increasing the more the superposition of effects is vanishing in the area close to the support (Y=0) and the numerical distribution of moments is below the curve determined in the analytic way.

On the other side (Y=0) the superposition is increasing with the increasing of the distance X. As mentioned above this effect is not taken into account in the analytical model and far from those areas the trend between the analytical and numerical is very similar and also the influence lengths are almost the same.

From this comparison is carried out that analytical and numerical solution show the same trend of behavior when compared in areas where the conditions are the same.

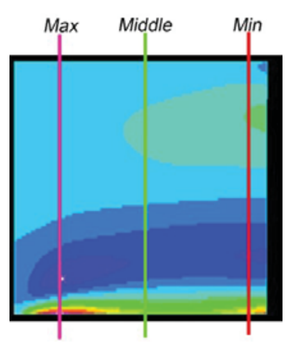


Figure 6.12 - Sections of edge disturbance plotting

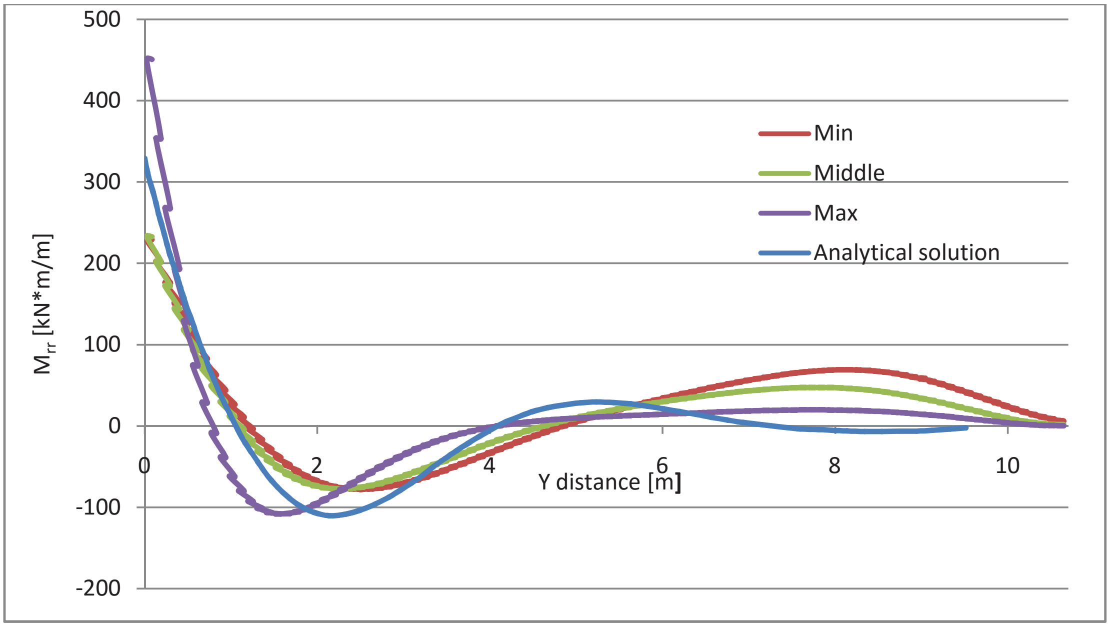


Figure 6.13 - Comparison Edge disturbance at the edge (Y=0)

6.2 Hinged Horizontal Edges

In the same way as for the clamped edges, the numerical analysis was performed also considering the horizontal edges as hinged so fixed only in displacement. A brief comparison of the results is shown in this chapter.

The changing of the boundary conditions is not affected significantly the vertical displacement Figure 6.14; the average values is 0.00286 [m] and the distribution pattern is almost the same as in the case with clamped edges.

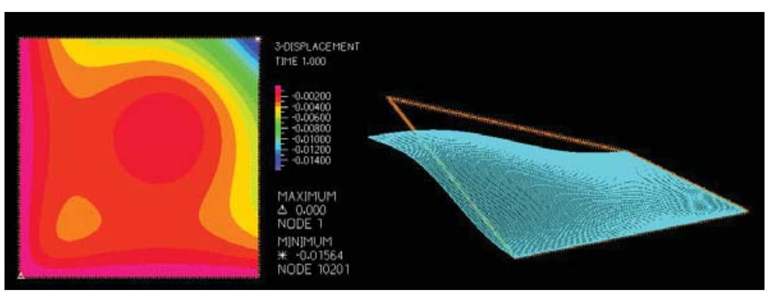


Figure 6.14 - Vertical displacement and structure deformation (magnification factor 150)

Also the shear stress distribution (τ_{rs}) is not changing significantly. The average value is 755 [kPa] which is 15% different from the analytical results. Also in this case this difference is considered to be acceptable and is due to the same reasons explained above (the FE model does not impose a-priori any assumption concerning the stress distribution and the stiffness of the edge beam). The range of stresses qualitatively defined in the case of clamped edges, is now interesting a wider area, confirming that in this case its distribution is becoming more uniform but not in a significant way (Figure 6.16).

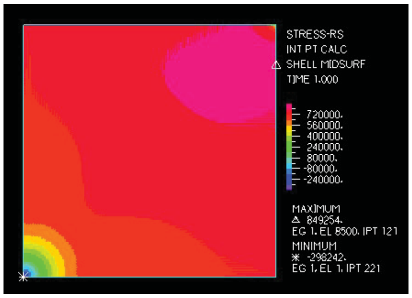


Figure 6.15 - Distribution of shear stresses rs

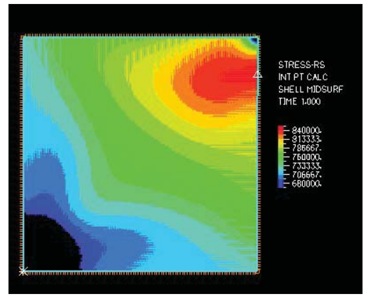


Figure 6.16 - Distribution of shear stresses rs – Range 660/850 [kPa]

Regarding the bending behavior the same considerations made before about the areas affected by the superposition of effects are valid also in this case and can be noticed in the plot of the bending moment M_{rr} (Figure 6.17). In this case the distribution of moments M_{rr} along the horizontal edges are zero, as the boundary conditions allows rotations. The edge disturbance has been plotted in the same sections (Max, Middle and Min) defined previously (Figure 6.12) and in the Figure 6.18 are compared with the analytical solution obtained for hinged edges.

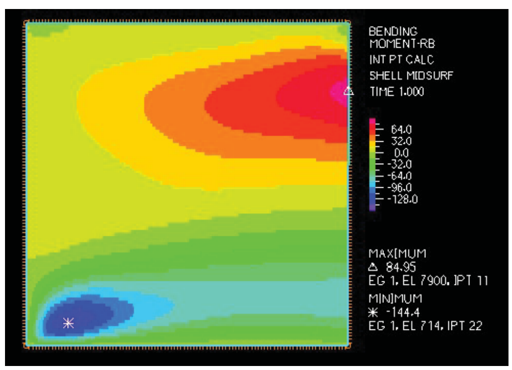


Figure 6.17 - Distribution of moments M_{rr}

From the comparison is possible to notice that, as in the previous case, the analytical and numerical solution have similar trend and influence length in the areas not affected by the superposition of the effects of edge disturbances.

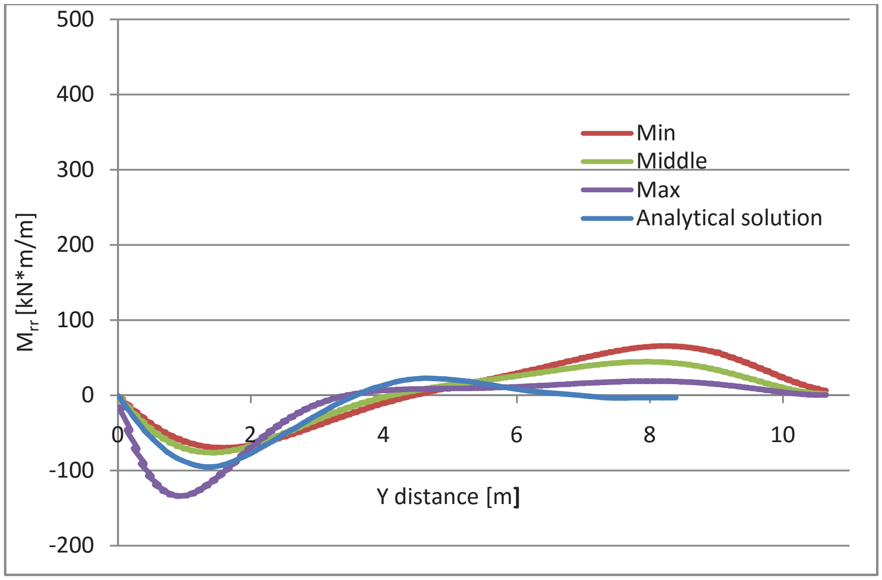


Figure 6.18 - Comparison Edge disturbance at the edge (Y=0)

6.3 Conclusions

In addition to the calibration of the model, its verification is also a very important step in any structural assessment since from this step depends the accuracy of the results. This allows to know if the model is following the theory that governs the problem. The comparison explained above underlines that the FE modeling process and its results show the same trend as the analytical solution. The shear stress differs between the two solution by 15% (maximum). Concerning the bending behavior, the graphs showing the edge disturbances in the two different boundary conditions, confirm the similar trend and influence lengths for the two solution. This similarity is considered in the areas less affected by the superposition effects as mentioned in the previous chapter.

The differences between the two methods find their reason in the fact that the analytical solution adopts certain simplifying assumptions, such as:

- constant distribution of shear stresses along the shell
- zero flexural and torsional rigidity of the edge beams
- bending moment constant along the edge
- edges far enough to avoid superposition of bending effects

Through this assumptions the analytical solution provides the exact result for the mathematical problem. The FE solution, on the contrary, does not impose a-priori these assumptions and it provides a approximate numerical result of the original differential equation. Since, the comparison showed that the percentage of difference of shear stresses is not significantly high (max 15% of difference is considered acceptable) and the results are close to each other in areas where the simplifying assumptions of the analytical solution are valid, the FE solution is considered verified by the analytical one.

7. COMPARISON SIMPLIFIED DESIGN METHOD AND NUMERICAL SOLUTION

As already explained in the Chapter 4 (Simplified Design Method) a numerical example was solved by both the simplified and the finite element method. The simplified solution is derived for a leveled structure, while the numerical solution through the finite element method is derived firstly for a leveled structure (as the simplified solution) and secondly for an inclined structure in order to evaluate if the simplified method can be used also for this case.

The mechanical properties of the plywood and of the edge beams and the elements used to describe them are the same as in the numerical model used for the verification process (Chapter 6 –Verification of the FE Modeling).

7.1 Leveled Shell surface

The load is applied as a vertical pressure on the shell along because in the simplified solution the vertical reactions are calculated as the distributed load (2.59 [kN/m^2]) times the area of the curved shell divided by two.

The boundary conditions of the structure consists in totally fixed displacements in the two points P1 and P4. With this boundary conditions the system is isostatic because the load and the structure are symmetric. In order to avoid rigid body motions during the numerical solution a kinematic relation was assigned to the points P2 and P3. This relation is expressed in the following equations and it means that the rotation of the point P2 has the same magnitude of the P3 rotation but opposite direction. This relation avoids the rigid body motion of the structure.

$$\varphi_{P2} = -\varphi_{P3} \tag{65}$$

The figures below show the generated mesh (Figure 7.1 and Figure 7.2) and the applied load (Figure 7.3).

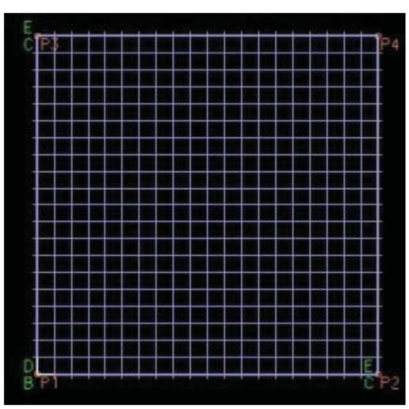


Figure 7.1 - Mesh - Top view

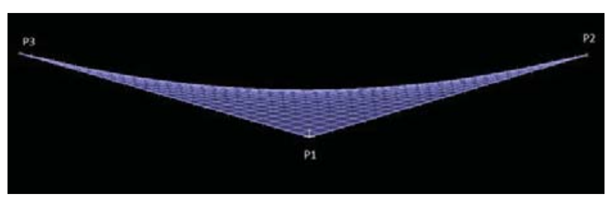


Figure 7.2 - Mesh - Frontal view

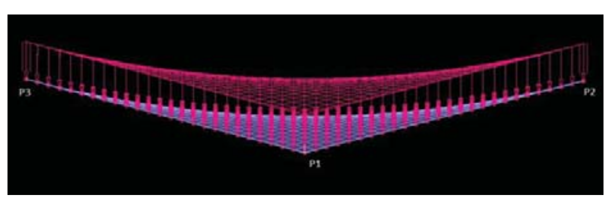


Figure 7.3 - Applied load - Frontal view

Through the deformation plot (Figure 7.5) is possible to notice how the kinematic relation avoids the rigid body rotation of the structure. The maximum displacement is localized in the vertices P2 and P3 and is around 0.42 [cm] (Figure 7.4).

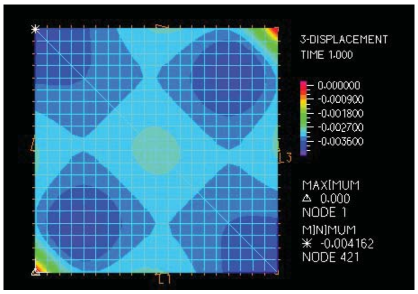


Figure 7.4 - Displacement Band Plot

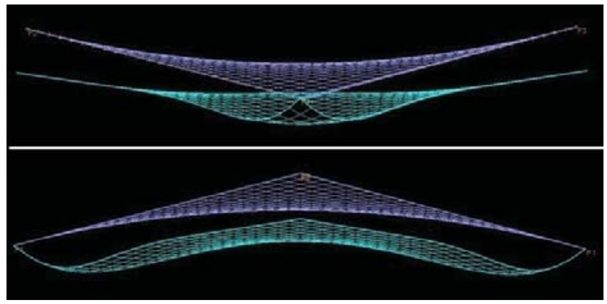


Figure 7.5 - Deformation of the structure (magnification factor 400)

The first step of the comparison between the numerical solution and the simplified solutions starts from the reaction forces. The Figure 7.6 shows that the reaction force F in the numerical solution is 669 [kN] and this result differ from the simplified solution by 0.2% instead the maximum compression of the edge members in the ADINA solution (Figure 7.7) is 2 % lower than the simplified solution (ADINA 457 [kN]; simplified solution 467 [kN]). This is mainly due to the fact that in the simplified solution the shear stress is considered constant in all the shell instead in the numerical solution it is not constant and it decreases close to the supports.

Figure 7.6 - Reaction force F

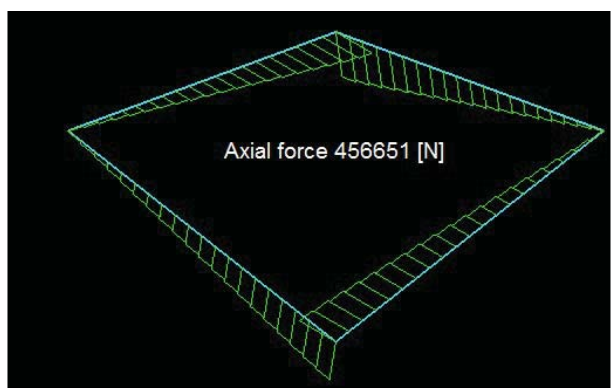
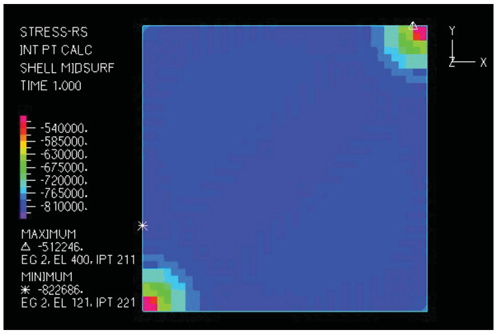


Figure 7.7 - Compression in the Edge members

The next comparison step passes through the shear (rs) and normal (rr, ss) stresses (local coordinate system in Figure 5.2 – Chapter 5). The distribution of shear stress is shown in the Figure 7.8 and is uniform far from the supports, instead close to the supports (P1 and P4) it decreases due to the boundary effects.

The qualitative comparison with the simplified solution has to be done with the stresses far from the supports since in the simplified solution the boundary effects are not taken into account. For this purpose in the Figure 7.9 is plotted the range of shear stresses in the area far from the supports. This range varies from -800 [kPa] to -822 [kPa], instead the result of the simplified solution (813 [kPa]) and the extreme values of this range differ from the simplified solution respectively by 1% and 1.5%.



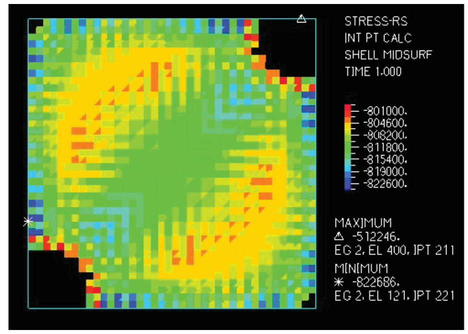
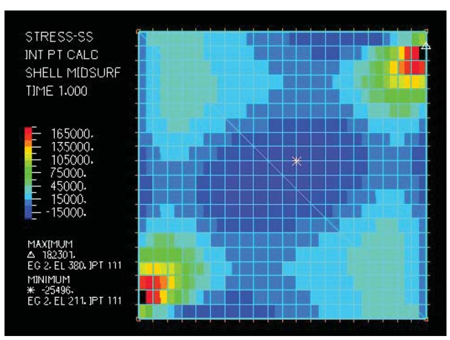


Figure 7.8 - Distribution of shear Stresses rs

Figure 7.9 - Distribution of shear stresses rs - Range -800/825 [kPa]

Concerning the normal stresses in rr (the stresses rr are not plotted because are symmetric with stresses ss) and ss (Figure 7.10 – ss stresses) they increase near the supports and the maximum value (in the supports P1 and P4) is 182 [kPa] and the minimum (in the central area of the shell) is -25 [kPa]. These two values are respectively 22% and 3% of the shear stress obtained by the simplified solution. This shows how the normal stresses are not negligible in the supports. The main area far from the supports is affected by stresses (rr and ss which vary from 50 [kPa] to -25 [kPa] (Figure 7.11). The extreme values of this range represent respectively the 6% and 3% of the shear stress obtained by the simplified solution. This highlights that the assumption of the shell working only in pure shear does not induce to considerable error in the main area far from the supports instead close to the supports the stresses rr and ss are between 22% and 3% of the shear stress and the assumption leads to an higher error bit still acceptable for a first and simple assessment of the behavior of the structure.



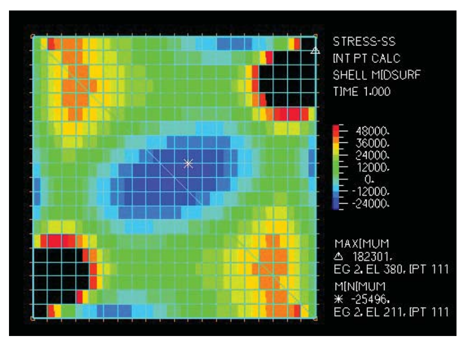


Figure 7.10 - Distribution of normal stresses ss

Figure 7.11 - Distribution of normal stresses ss, range 50/-25 [kPa]

This qualitative comparison shows that the simplified solution provides results which are really close to the numerical solution in the main area far from the supports and the edges, instead close to this areas, mainly in the supports, the error increases. The Table 7.1 summarizes a quantitative comparison where all the values are taken into account (supports values are not excluded) for the computations of the average stresses. Is possible to notice that the average values of the stresses in the numerical model are almost the same as the simplified solution and this confirms the accuracy of the simplified rules for structures that present the same configuration as the one analyzed in this chapter.

Table 7.1 - Comparison Simplified solution - Numerical solution

		Simplified solution	**Numerical solution**		**% of difference**
Reaction **F**	[kN]	670,41	669		0,2%
Edge compression **C**	[kN]	466,86	459		2%
Shear stress **rs**	[kN/m^2]	813	Max	-512	[-]
			Min	-823	[-]
			Average	-811	0,2%
Normal stress **rr - ss**	[kN/m^2]	0	Max	182	[-]
			Min	-25	[-]
			Average	10	1,2%*
* indicates that is not a percentage of difference but the percentage of the shear stress.					

7.2 Inclined Shell Surface

In order to have a further understanding on the reliability and accuracy of the simplified solution, the comparison process explained above was made also with the structure numerically solved in its real position and dimensions, so no rotated but tilted as shown in the Figure 7.12.

The mechanical properties and the load applied are the same as in the previous model (structure rotated in horizontal position), instead the boundary conditions are different. In the point P1 and P3 all the displacement components are fixed instead in the point one is fixed only the vertical displacement. The Figure 7.13 shows the boundary conditions and the load applied.

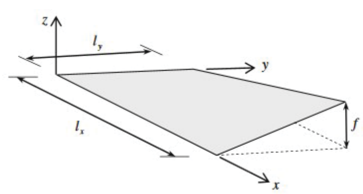


Figure 7.12 – Inclined Shell Surface

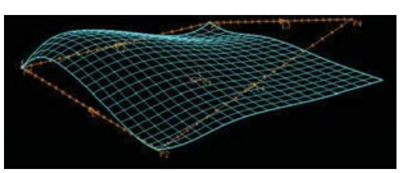


Figure 7.14 - Structure deformation

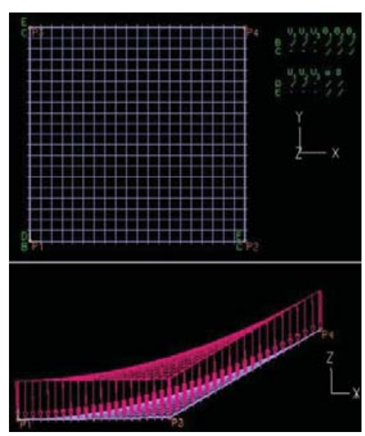


Figure 7.13 - Boundary conditions (above) and applied load (below)

This structure configuration is characterized by three reactions, two in the supports P2 and P3 and one vertical in the support P1 (Table 7.2).

Table 7.2 - Reaction magnitude

Support	Reaction magnitude	
P1	3,714	[kN]
P2	568,496	[kN]
P3	568,496	[kN]

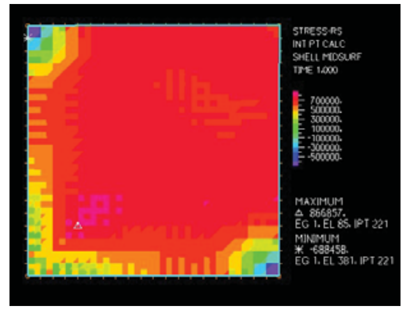


Figure 7.15 - Shear stress rs distribution

The force reaction in P1 is 0.7% of the reactions in P2 and P3, this highlights how the influence of the support P1 is low (in terms of reaction forces) and that the forces in the supports P2 and P3 does not change significantly (15%) respect the previous case (structure rotated in horizontal position F is 669 [kN]).The maximum compression in the edge members has a maximum value of 417 [kN] which differs by 11% from the simplified solution.

Due to the configuration and boundary conditions of the structure the deformation is different from the previous case and is shown in the Figure 7.14.

Regarding the shear stress (rs) the Figure 7.15 shows an overview of its distribution, and is possible to observe that also in this case shear stresses decrease close to the supports P1 and P2, instead the maximum value (867 kPa) is close to the support P1 and this is due to the deformation of the structure that concentrates the in-plane maximum shear strain in this area.

Concerning the main area far from the supports, it is interested by a range of stress from 550 [kPa] to 850 [kPa] (Figure 7.16). Comparing with the previous case the range is getting wider, pointing out that the assumption of constant shear stress in the shell is affected by higher error in this case, but still the value of the simplified solution is inside this range.

As it was for the shear stress, also concerning normal stresses rr and ss (Figure 7.17) the area close to the support P1 is affected by concentration of stresses and the maximum value is -1304 [kPa] which is 60% bigger than the shear stress and this means that those stresses can not be neglected. Considering only the area far from the supports the range of normal stresses is from 350 [kPa] to -450 [kPa] (Figure 7.18). The two extreme values of the range represent respectively the 43% and the 55% of the shear stress obtained by the simplified solution,

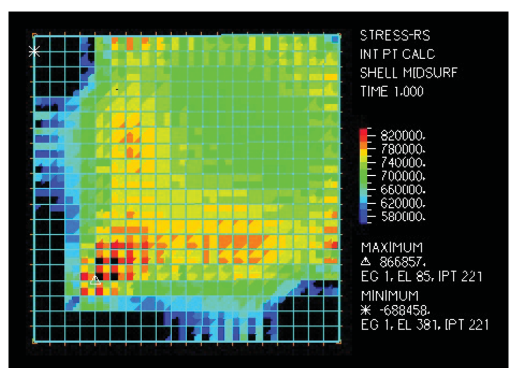


Figure 7.16 - Distribution of shear stresses RS - Range 550-850 [kPa]

so the assumption of no presence of normal stresses lead to a significant error. Particular relevance have the negative values which correspond to compression because the compression stresses can lead to buckling.

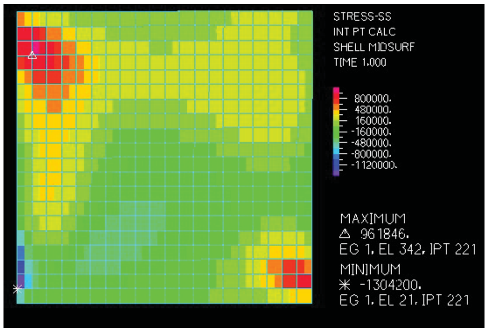


Figure 7.17 - Distribution of normal stresses ss

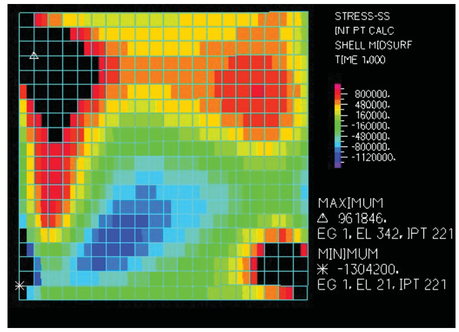


Figure 7.18 - Distribution of normal stresses ss, range 350/-450 [kPa]

The Table 7.3 represent the quantitative comparison between numerical and simplified results, as it has been done in the previous case of the horizontal structure.

Table 7.3 - Comparison Simplified solution - Numerical solution

		Simplified solution	**Numerical solution**		% of difference
Reaction **F**	[kN]	670,41	568		15%
Edge compression **C**	[kN]	466,86	417		11%
Shear stress **rs**	[kN/m^2]	813	Max	867	[-]
			Min	-688	[-]
			Average	726	11%
Normal stress **rr - ss**	[kN/m^2]	0	Max	962	[-]
			Min	-1304	[-]
			Average	146	18%*

* indicates that is not a percentage of difference but the percentage of the shear stress.

7.3 Conclusions

The aim of the comparison between the simplified solution and the numerical solution is to verify the reliability of the simplified designing method that can be very convenient as a fast structural assessment of stresses and reaction forces.

The first case of comparison (Leveled Shell Surface) shows that the simplified solution seems to be a perfect tool for obtaining a first idea of the behavior and stress distribution of structures that presents boundary conditions and geometry similar to the hyperbolic-paraboloid shell structure analyzed in this case, for which the simplified solution has been developed. The values summarized in the Table 7.1 present a maximum difference between the two solutions of 2%.

In the second case the comparison was done with the inclined structure and the numerical results obtained showed the limits of the simplified method. In this case the normal stresses increase significantly (due to the slope and to the boundary conditions) and they can not be neglected, in particular when they correspond to compression.

The limit of the simplified solution is represented by the geometrical conditions, as it can be applied only to leveled structures. Taking this into account it still remains a fast way to have a first approximation of the shear stresses, reactions and compression in the edge members, but further structural analysis are needed for structural designing or assessments.

8. NAKASHIMA ARTS BUILDING

8.1 Historical Context

The Nakashima Arts Building was born in the years when timber shell structures where reaching the peak of popularity (1950-1970) in the United State and Europe (specially in Britain). The interest on this type of structures was on their functional qualities, efficiency (in terms of material and span), and elegant shapes. Until these years, the shell structures were mainly in reinforced concrete, since their behavior and concept was well established in Europe by 1939. In a process of innovation, the studies started to be more focused on the application of new material as timber. Important was the case of Britain where the studies on timber hyperbolic paraboloid roofs were carried out by the Timber Development Association (TDA). This association was transformed from a publicity body of the timber trade into a research and development organization (Booth, 1997).

In the same way, university researches and conferences increased the interest in hyperbolic paraboloid structures in the United States. A result of this period of researches and studies is the hyper roof built by Catalano in Raleigh, North Carolina. In the same years of Nakashima's work, the Department of Architecture and Architectural Engineering of the University of Kansas started a research project on hyperbolic paraboloids using plywood (Ballester, 2015).

Figure 8.1 - Catalano's hyperbolic paraboloid roof (Ballester, 2015)

This brief introduction of the historical context is meant to explain that the Nakashima Arts Building was built in a period of a continuous innovation process through research projects and real applications as the Catalano's roof.

8.2 Architectural Description

The Nakashima Arts Building is part of woodworking complex built between 1960 and 1975 in new Hope, Philadelphia (Figure 8.2). The Arts Building, Cloister, Pool House and Reception House are clear examples of the skills and abilities of the furniture designer and architect George Nakashima. The architect's work represent a fusion between the traditional Japanese craft and the modern architectural influences of the mid-twentieth century.

The Arts Building and the Cloister were built, as art gallery and museum, between 1964 and 1967, and they are directly connected by a covered path.

Both buildings are located in an isolated area, in the east part of the property where the slope starts to decrease.

The Arts Building is composed by a hyperbolic paraboloid shell roof made of plywood. The two main facades are oriented respectively in west and south directions, and the main entrance is located in the corner between the two facades.

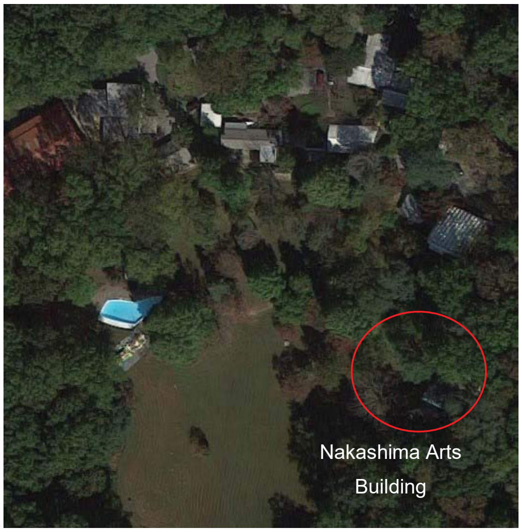


Figure 8.2 - Nakashima's property in New Hope

(www.google.it/maps)

This building shows the architect's mastery on the use of different material. Stone masonry, reinforced concrete slab, plywood shell and timber edge beams find in this building a perfect equilibrium and harmony between them. The maximum high of the Arts building is around 6,83 meters. The main entrance represent a transition area from the exterior to the interior space. It is characterized by height of 2,50 meters, covered by a ceiling in reinforced concrete grid. The same ceiling is a terrace in the upper level.

The two facades, west and south, emphasize the lightness of this structure. The sliding doors and windows ensure a bright inner space where the relation with the exterior environment is always present through the view and the material (timber).

In the 2014 the Nakashima's property was included on the World Monuments Watch, and World Monuments Fund is collaborating with the Nakashima Foundation for Peace with the aim of creating a sustainable plan, according to the original idea of George Nakashima (World Monuments Fund, 2016).

The elegance and the integration between the materials is shown in the Figure 8.3 (south elevation) and Figure 8.4 (internal view).

Figure 8.3 - South elevation

(www.nakashimawoodworker.com)

Figure 8.4 - Internal view

(www.nakashimawoodworker.com)

8.3 Geometrical Description

The geometrical survey has been carried out by Mr. Cesar Bargues Ballester and the drawings were provided through the professor David Biggs. The Arts Building is about 6,83 meter tall and in plan has a square shape of 10,67 meters wide. The structure of the building is composed by different elements that interact together. The structural elements can be listed as the following:

- *Plywood shell roof:* the shell roof has an hyperbolic paraboloid shape and is obtained by lifting the southwestern corner 4,27 meters high (Figure 8.5). The structure consist of three plywood layers (each 1,6 cm thick) overlapping each other's according to the pattern defined in the Figure 8.6.

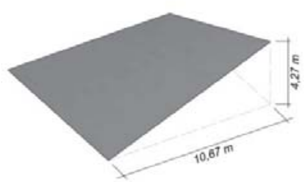


Figure 8.5 – Dimensions of the shell roof

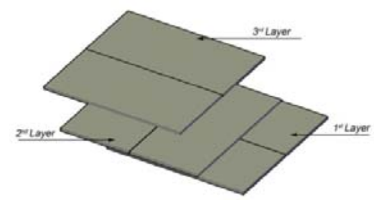


Figure 8.6 – Pattern of the plywood layers

- *Buttresses:* the two buttresses aims as supports for the two taped timber beams. The thrust coming from the edge beams as compression is directly transferred to the stone masonry buttress. Their thickness is around 0,5 meters and they present a triangular shape as is common for this type of structural elements.
- *North and East external walls:* on the north and east side the roof is supported by two external masonry walls. Their height is around 2,50 meters and a thickness of around 0,45 meters.
- *Tilted edge beams:* in the south and western part the roof is supported by two tapered and tilted edge beams. The beams are in timber and they present different cross section from the bottom to the top. This is due to two facts: firstly for having less mass far from the buttress support, and the second reason is because the beam needs to follow the geometry of the shell. The Figure 8.7 shows two sections (bottom and top) of the tapered edge beams.

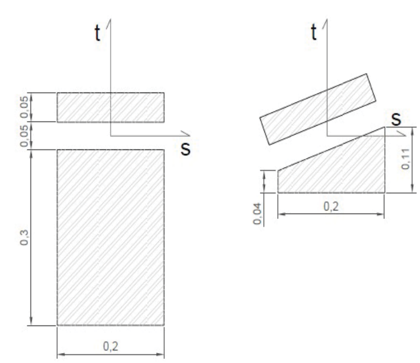


Figure 8.7 – Bottom (left) and Top (right) sections of the tilted edge beams (measures in meters)

- *Vertical Posts:* beneath the two tilted edges are placed three vertical timber posts. Their efficiency is investigated through the numerical analysis. One is placed in the southwestern corner of the shell and is characterized by a cross section of 0,10 x 0,15 meters. The other two posts have same cross section of 0,10 x 0,10 meters and are, respectively, placed beneath the two tilted edges at a distance of 4,57 meter from the southwestern corner.

- *Walls and slab of the main entrance:* the main entrance of the building is in the southwestern corner of the building. The south exterior wall is made by 30 cm concrete block units (Bargues Ballester, 2015). On the west side the wall is a concrete slab reinforced by concrete ribs. The interior wall of the main entrance is a stone masonry wall. This space is 2,50 meters high and is covered by a ceiling of reinforced concrete grid.

In Figure 8.8 is shown an axonometric exploded view of the structural elements that compose the structure. In Apendix 1 is shown the plan and a cross section (drawings developed by Mr. Bargues Ballester and provided by professor David Biggs) of the Nakashima Arts Building.

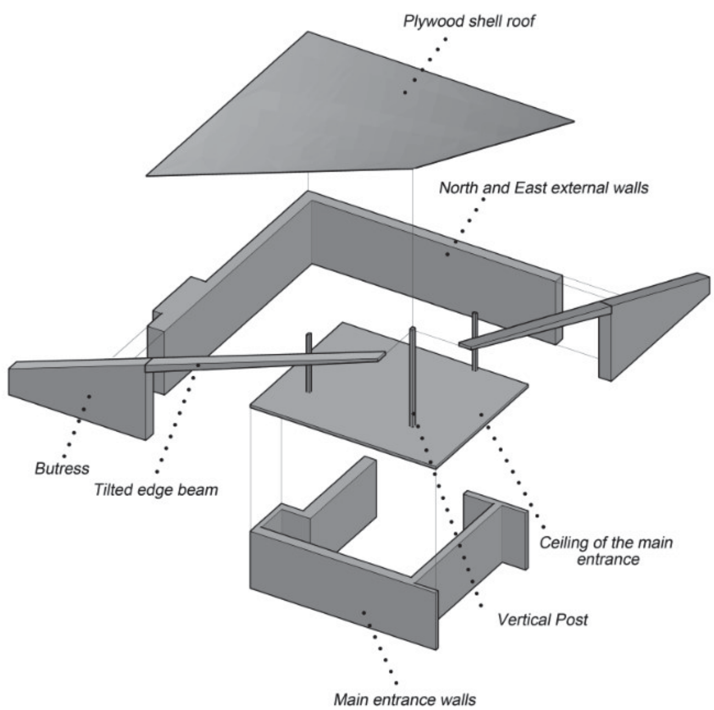


Figure 8.8 – Exploded view

8.4 Damage Survey

The damage survey is more focused on the timber elements with the aim of defining the condition of specific wood elements in the building. The work has been carried out by the wood scientist for A&A, Mr. Ron Anthiny and Mr. Cesar Bargues Ballester of the University of Pennsylvania School of Design. The work has been focused on the following elements:

- South and West edge beams
- Southwest corner post
- Plywood roof diaphragm

The condition assessment of the timber elements is carried out through different methods as: species identification, visual inspection, probing, moisture diagnosis and deterioration quantification though a limited resistance drilling technique.

In this chapter are merely expressed the results of the work done by the experts mentioned above and provided by the professor David Biggs in a report form (Anthony & Associates, 2016).

Findings:

- The flowing wood species characterize the elements analysed:
    - Douglas-Fir: edge beams
    - Eastern White Pine: corner post
    - Baldcypress: ceiling ribs
- Patches of moss have been detected in the roof. However they are not connected to the membrane or diaphragm below, but only looely connected to the gravel. Is suggested to remove them periodically in prevent the developing of vulnerable situations(Figure 8.9 and Figure 8.10).

Figure 8.9 – Patches of moss on the roof (Anthony & Associates, 2016)

Figure 8.10 - Moss in-situ, with awl for scale (Anthony & Associates, 2016)

- West and South tilted edge beams , and the southwest corner post seems to be in good condition and no deterioration process is affecting them. Edge beams are classified as Douglas-fir Select Structural, Beams and Stringers. The corner post is classified as Eastern White Pine Select Structural, Structural Joists and Planks.
- Four posts in the south façade are characterized by deterioration at the base (Figure 8.11). The southeast is the one affected more and a repair work is suggested.

Figure 8.11 - Damage at the base of the southeast post
(Anthony & Associates, 2016)

- Due to heavy rain, it was not advisable to investigate the plywood diaphragm by opening a probe area. Is suggested to proceed with this investigation after the structural analysis and when the weather conditions do not compromise the integrity of the structure.
- Ribs are placed in the interior surface of the shell roof and aims to cover the connection between the plywood panels. They are in good condition, except for a joint failure in one rib (Figure 8.12). Since they have no structural meaning the behavior of the roof is not affected by this failure.

Figure 8.12 - Joint failure in the rib (Anthony & Associates, 2016)

- The environmental conditions did not allow a proper investigation of the connection between the southwestern corner post and the edge beams (Figure 8.13). Is suggested to assess this connection in order to ensure the structural function and integrity of the post.

Figure 8.13 - Connection between edge beams and corner post (Anthony & Associates, 2016)

9. MECHANICAL CHARACTERIZATION

The roof of Nakashima Arts Building is composed by plywood layers bounded together with adhesive and nails for the shell structure. The knowledge of the mechanical properties is of critical importance for their proper use and for the understanding of their behavior. The structural elements that define the behavior of the roof structure are:

- Plywood roof diaphragm
- Tilted edges beams
- Vertical posts

The mechanical properties are defined thorough the identification of the wood species and then its grading. This last step depend on the size, specie, growth characteristics, exposure and load condition. The procedures have been done by Mr. Ron Anthony, Mr. Cesar Bargues and Mr. David Biggs. The results were provided by the Professor David Biggs. The following Table 9.1 summarize the species of the structural elements mentioned above and the codes used for their structural grading and determination of the allowable design values. The allowable design values are based on test data and procedures defined by the America Society for Testing and Materials (ASTM) and are shown in the Table 9.2 and Table 9.3 for all the structural elements.

Table 9.1 - Species and Referring codes of the structural elements

Structural element	Specie	Code
South Edge beam	Douglas-fir	Western Lumber Grading Rules (2011)
West Edge beam	Douglas-fir	Western Lumber Grading Rules (2011)
Posts	Eastern White Pine	Standard Grading Rules for Northeastern Lumber (2013)
Plywood	Ponderosa Pine	Plywood Design Specification (1997) - APA

Table 9.2 - Mechanical properties for Edge Beams and Posts

Structural Element	Grade	Extreme Fiber Stress in Bending Single Member	Tension Parallel to Grain	Horizontal Shear	Compression Perpendicula - Parallel to Grain		Modulus of elasticity
		Fb	Ft	Fv	Fc⊥	Fc	E
		[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[Gpa]
South and West edge beams	No.1	8963	4309	1137	3585	5654	8,274
Posts	No.2	3103	2068	862	2413	2241	6,205

Table 9.3 - Mechanical Properties of the Plywood

Structural Element	Grade	Fb [kPa]	Ft [kPa]	Fv [kPa]	Fs [kPa]	Fc⊥ [kPa]	Fc [kPa]	G [Gpa]	E [Gpa]
Plywood	EXP 1,2 or INT	8274	8274	827	331	1448	6825	0,379	8,274

Fb: Extreme Fiber stress in Bending

Ft: Tension in Plane of Plies (ar 45° to face grain use 1/6 Ft)

Fv: Shear Through the Thickness (at 45° to face grain use 2Fv)

Fs: Rolling Shear in the Plane of Plies (at 45° to face grain use 1-1/3 Fs)

Fc⊥: Bearing on Face (perpendicular to Plane Plies)

Fc: Compression in Plane of Plies (at 45° to face grain use 1/3 Fc)

G: Shear Modulus Through the Thickness (at 45° to face grain use 4G)

E: Modulus of Elasticity in Bending in Plane of Plies

10. DEFINITION OF LOADS AND LOAD CASES

10.1 Definition of Acting Loads Type

The loads that acts in the roof structure of the Nakashima Arts Building are mainly three types: the dead load of the plywood, the permanent load of all the covering materials, snow load and the wind load. Since the roof is not practicable there is no live load acting. Moreover, is considered also the load of the ribs placed underneath the roof with the aim of covering the connections between the plywood panels. Table 10.1 shows the intensities of all the loads considered.

Table 10.1 – Load Type and related intensity

Load Type	[kN/m2]
Plywood (3layers)	0,287
Ribs	0,024
Celotex (2 layers)	0,024
Asphalt felts	0,096
Marble chips	0,718
Snow	1,436
Wind	1,197

10.2 Definition of the Load Cases

The linear elastic analysis are performed considering five different configurations of load cases. The first three load cases involve the snow load, instead the last two concern the wind load. They are defined as following:

- LC1: full dead load and snow load uniformly distributer all over the shell roof.
- LC2: full dead load and quarter of the snow load swept into the northeast half area of the roof (Figure 10.1)
- LC3: full dead load and half of the snow load swept into the northeast half area of the roof (Figure 10.2)
- LC4: full dead load and sixty percent of the wind load acting as uplift uniformly all over the shell roof
- Lc5: full dead and the wind load acting as downward into the southwestern half area of the roof (Figure 10.3)

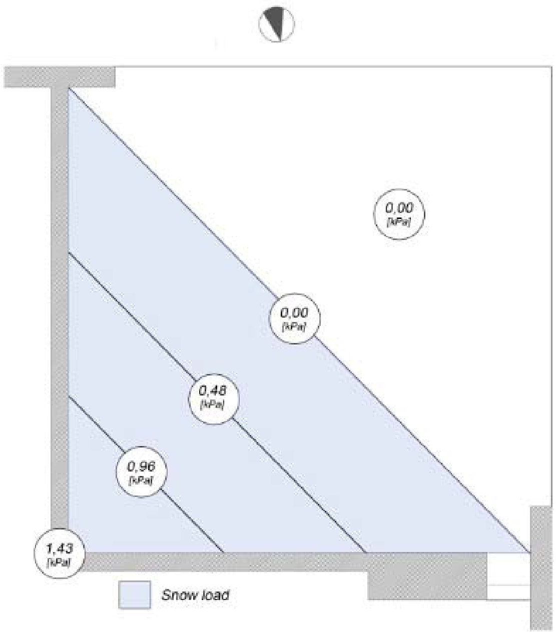


Figure 10.1 - LC2

Figure 10.2 - LC3

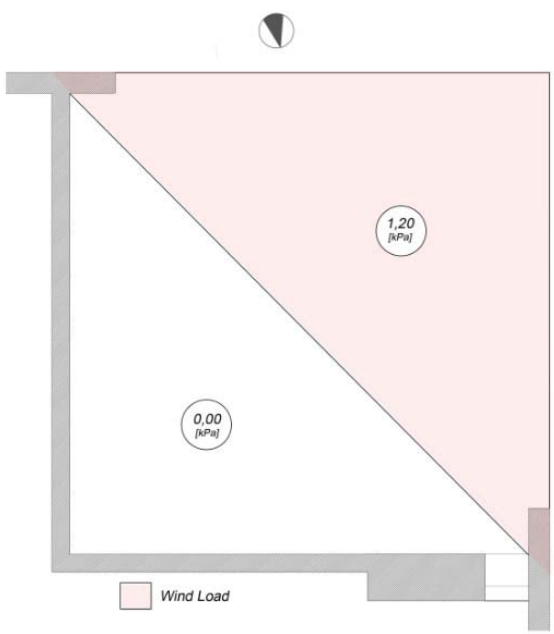


Figure 10.3 - LC5

11. FE MODELING AND ANALYSIS

The modeling and the analysis are computed, through the software ADINA, as already mentioned in the chapters above. The structural analysis of the structure is preceded by the important step of the model verification (Chapter 6 – Verification of the FE Modeling) which consists on comparing the numerical results with the analytical ones. Once the model was verified, it was possible to proceed with the structural assessment of the structure in different configurations and subjected to different load cases. Since the modeling needs to describe in the best way possible the real behavior of the structure, different aspects are taken into account and shown in the following chapter *Modeling strategy*.

More important than obtaining the results is their interpretation and discussion, indeed the following chapter *Methodology of results analysis* explains the different steps through which the results are analyzed.

Through the strategy of modeling and the methodology of interpretation, the results of the linear elastic analysis are shown in the chapter *Effect of boundary conditions and load cases in the structural behavior of the shell*.

11.1 Modeling Strategy

The proper structural analysis and “sensitivity” analysis required a refined model where different aspects (simplified in the step of verification of the model) are considered in order to simulate as much as possible the real structural behavior of the roof.

The model used in the “sensitivity” analysis has a density of 72x72 in order to catch with a good approximation the bending behavior. The plywood shell structure is modeled by 4-nodes shell elements, while the edge beams by 2-node Hermitian beam elements (Chapter 5 – FEM concept).

The second aspect that is taken into account in the refined modeling concern the edge beams. The two tilted edge beams present a variable cross section along their length (Figure 11.1). Moreover, the edge beam is shaped in the way to follow the geometry of the hyperbolic-paraboloid roof and the connection between this edge beams and the plywood shell is stiffened by the addition of boards above the shell.

Due to this, the moment of inertia, which influence the rigidity of the beam, is different in every section of the beam. This was taken into account by discretizing the beam in twelve part and every part is described by the median section (Figure 11.2). For the twelve sections the moments of inertia I_t, I_s and the product of inertia I_{ts} have been calculated and implemented in ADINA software as a beam element with generic section (local axis of the beam elements shown on Figure 5.4 Chapter 5). In the Appendix 2 is shown the table with the inertial properties of every cross section considered.

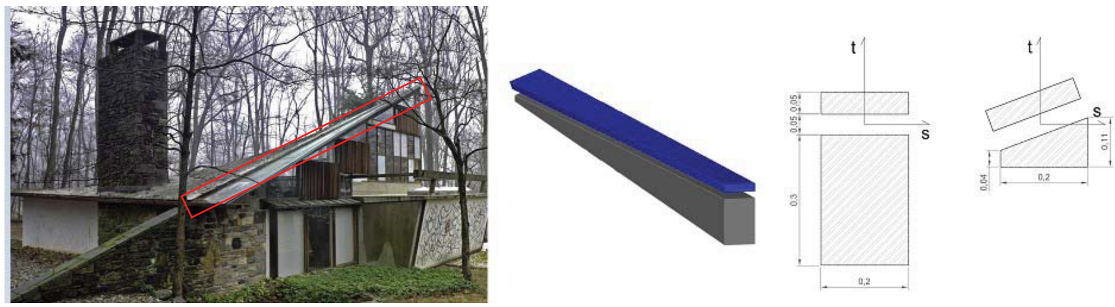


Figure 11.1– Localization of the tilted edge beams (left); scheme of tapered edge beam (center); top and bottom cross sections (right)

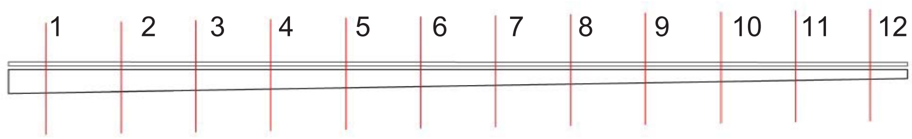


Figure 11.2 – Discretization of the edge beam

In the two previous preliminary model all the loads are applied respectively in the global z-direction (for comparison with the simplified solution) and normal to the surface (for the model verification with the analytical solution). In the refined analysis concerning the effect of the different configurations the loads are treated depending their type.

The dead load is applied in the global z-direction, the wind load is applied as normal to the surface, while the snow load is given as force intensity per projection of area on which it acts to horizontal plane. For curved surface the snow acts with a higher intensity where the curvature is almost zero (Figure 11.3). In the modeling this distribution is considered by applying the load as z component only which correspond to the distribution defined in the Figure 11.4.

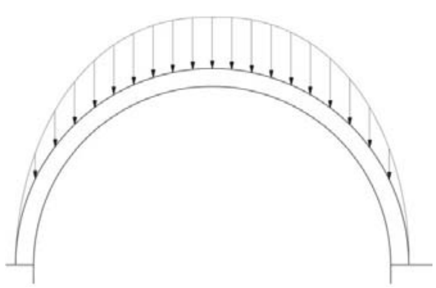


Figure 11.3 - Distribution of snow in the Arch

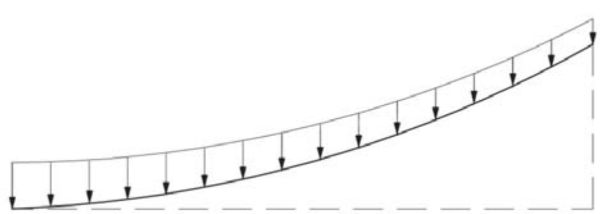


Figure 11.4 - Distribution of snow in the Shell

The last aspect that have been considered in the refined model concern the post. In the configurations where they are considered as structural elements the description of their behavior is done by 2-node truss elements (Chapter 5 – FEM Concept).

11.2 Methodology of Results Analysis

The results of the linear elastic analysis are shown through four different parameters:

- Maximum and minimum principal stresses (denoted as stress P1 and stress P3)
- Vertical displacement of the diagonal
- Shear through the thickness τ_{st}
- Axial force in the Posts

The principal stresses P1 and P3 are analyzed and compared between the different load cases and boundary conditions in two different steps:

- *Qualitative comparison*: where the stresses are plotted on top, mid and bottom surface and their distribution is analyzed in order to find the maximum ones and also the ones that can represent critical situation due to their location and concentration. Moreover the stresses are analyzed also in regarding to the principal direction in which are acting since the APA () defines the strength of the plywood as a function of the direction in which the stress is acting.
- *Quantitative comparison*: in this step the values defined through the qualitative comparison are compared with the strengths of the plywood material (defined in the Chapter 11 – Mechanical Characterization). The APA (The Engineered Wood Association, 1997) used as a reference for the definition of the mechanical properties defines the compressive (Fc) and tension (Ft) strengths depending on the direction of the principal stress. When it is acting at 45° to face grain the tensile strength to be used is Ft/6, while the compression is Fc/3. Concerning the tensile behavior the principal stress has been compared only with the strength Ft/6 since in every configuration and every load case the critical or maximum tensile stress is acting at 45° to the face grain of the ply wood.

  In compression behavior two maximum values are considered: one where the stress is acting perpendicular to the face grain (Max P3) and one where is acting at 45° (Max 45P3). Thorough this quantitative comparison the critical configurations are identified.

The shear through the thickness is analyzed by comparing the maximum values with the material strength. The band plots are shown in the Appendix 3.

Concerning the posts their results are analyzed in terms of maximum compressive force between the all configurations and load cases. Since the sections of the posts are different, the maximum compressive force is evaluated for the post in the corner between the tilted edges and for the two lateral posts. The maximum compression is than compared with the strength and also with the critical buckling load.

11.3 Effects of Boundary Conditions and Load Cases in the Structural Behavior of the Shell Roof

The configurations studied through the linear elastic analysis are four and depend on the boundary conditions of the horizontal edges and if the posts are considered as structural elements or not. For every configuration is subjected to five load cases. The band plots of the results are shown always in the plan X-Y and all the considerations on localization of stresses are referred to the orientation shown in the Figure 11.5.

The first three load cases concern the different distribution of the snow load, while the remaining two (LC4-LC5) refer to the wind load. For this reason the analysis and the comparison of the results is done between the load cases that involve the same type of load (Snow – LC1, LC2, LC3; Wind – LC4-LC5).

As mentioned in the chapters above the wind is considered as acting in two different ways. The first is a uniform uplifting of the roof (LC4). The second is a uniform downward on half area of the roof (LC5).

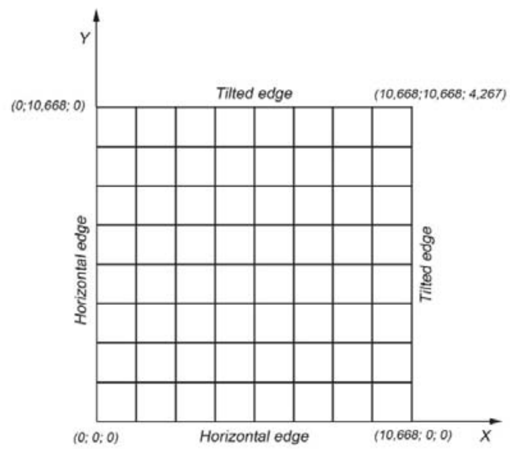


Figure 11.5 - Orientation of results band plots

Concerning the first wind load case (LC4) its intensity is not enough to have a real uplifting because the dead load of the roof has a higher value. However this load case has been analyzed anyway because the wind and the dead load act in different way. The first is acting in the global z-direction, while the second is acting normal to the surface so the final load will have a different direction in every point of the shell.

The load cases are analyzed for each configuration, with the configurations summarized as following:

- *1st Configuration*: clamped horizontal edges and posts not considered
- *2nd Configuration*: hinged horizontal edges and posts not considered
- *3rd Configuration*: clamped horizontal edges and posts considered
- *4th Configuration*: hinged horizontal edges and posts considered

These configurations were considered because they represent extreme cases as it is not clear how the connection to the supporting walls actually works and whether the posts provide any structural support.

11.3.1 First Configuration - 1st

LC1-LC2-LC3

As a first step the principal stresses P1 and P3 has been computed for all the three load cases and the results in term of maximum values are shown in the Table 11.1.

Table 11.1- Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% difference between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC1	Max	-3,60	1,02	72	0	0
	Min	0	0			
LC2	Max	-1,80	0,60	67	-50	-42
	Min	0	0			
LC3	Max	-1,87	0,92	51	-48	-10
	Min	0	0			

The uniform distribution of the snow load causes the maximum values of the principal stresses (P3 – compression; P1 – tension). This load case is also characterized by the highest percentage of difference between the two principal stresses. Moving from the uniform distribution to the distribution where half of the snow load is swept with a triangular distribution onto half of roofs area (LC3) the maximum stresses decrease (-48%) and the difference between each other's is getting lower (passing from 72% in LC1 to 51% in LC3). The comparison can not be done only in terms of maximum stresses because they are concentrated in one area and a wider view in all the structure is needed. For this purpose the band plots of the principal stresses (in the middle surface of the shell structure) for all the load cases have been computed and are shown in Figure 11.6, Figure 11.7 and Figure 11.8. The same range of stresses is used in all the contour plots and is defined through the maximum values.

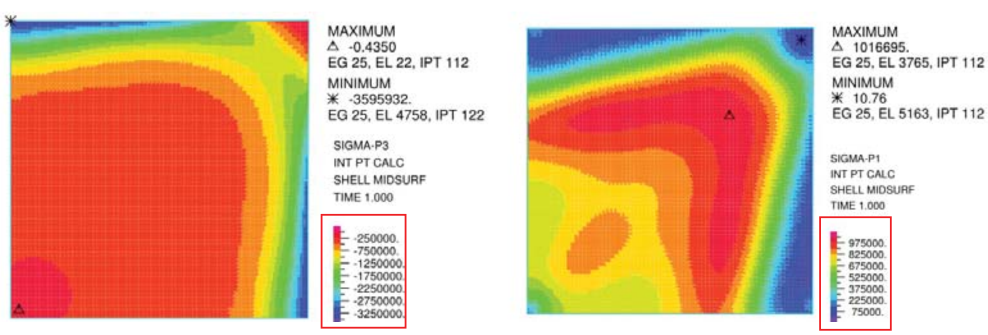


Figure 11.6 - LC1 (P3 left, P1 right) Midsurface [Pa]

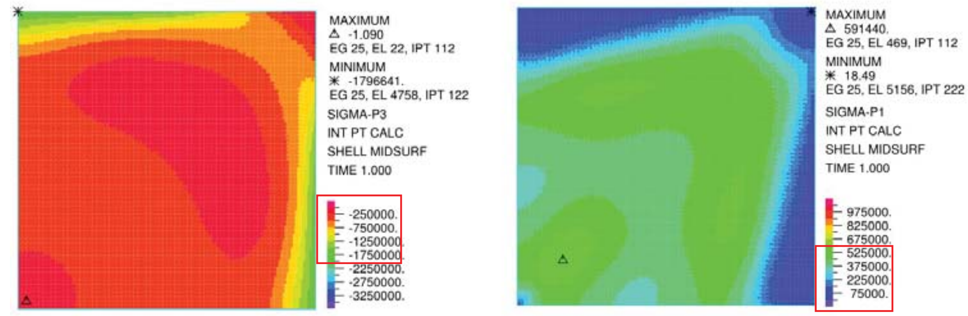


Figure 11.7 – LC2 (P3 left, P1 right) Midsurface [Pa]

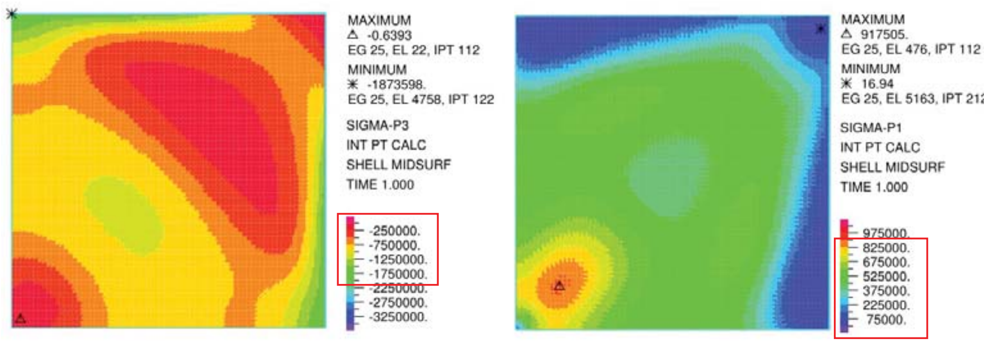


Figure 11.8 – LC3 (P3 left, P1 right) Midsurface [Pa]

The mid surface band plots evidence that in the first load case the compression is more concentrated in the supports between the tilted and horizontal edges, while in the main of the rest area, the compression is quite low and uniform. The stress P1 which concerns the tension, in the load case LC1 is spread in two main areas, perpendicular to the horizontal edge beams and the maximum value is in the corner between the two tilted edge beams. From the figures above is possible to underline that moving from the LC1 to the LC3, the compression is becoming more heterogeneous and is interesting not only the area of the supports between the tilted and horizontal edge beams but also the central area of the shell. The tension P1 is becoming more concentrated in the corner between the two horizontal edges.

For a better understanding of the behavior and also of the bending effects the principal stresses have been plotted also on top and bottom surfaces for load cases LC1, LC2 and LC3 (Figure 11.9, Figure 11.10 and Figure 11.11).

The band plots through the thickness highlights that in all the load cases the compression is concentrated close to the supports between tilted and horizontal edges.

Concerning tension, the first load case is concentrating the stresses differently on top and bottom surface. On top surface is more concentrated in the corner between the tilted edges (indicated by A in Figure 11.9), while on bottom surface is more concentrated in the opposite corner (B in Figure 11.9). The concentration of tensile stresses in two opposite areas underlines the structures' bending behavior for this load case.

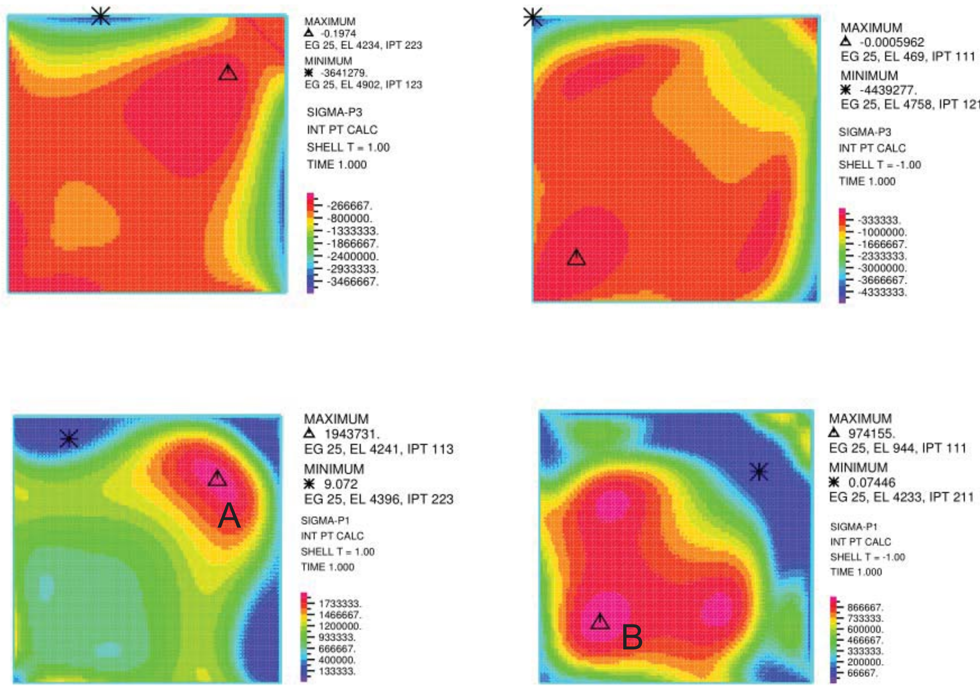


Figure 11.9 - LC1: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

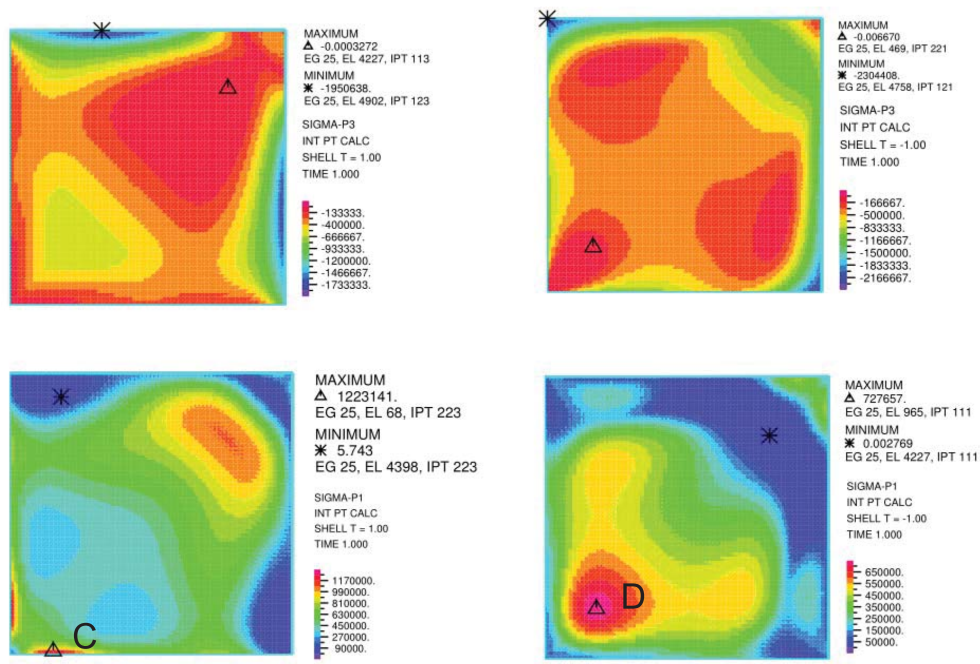


Figure 11.10 – LC2: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

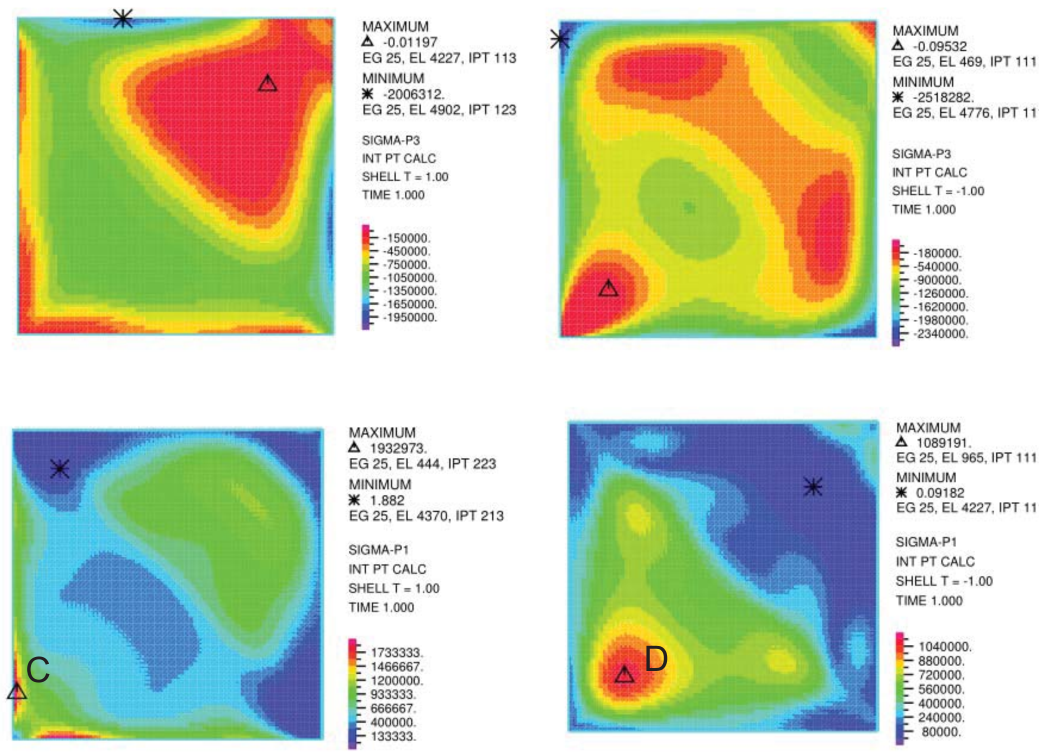


Figure 11.11 - LC2: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

The second and third load cases show similar behavior and distribution of stresses. In terms of tension it is localized differently on top and bottom surface. On top surface is concentrated in the horizontal edges close to the support (C in Figure 11.10 and Figure 11.11), while in bottom surface is not in the horizontal edges but close to their shared corner (D in Figure 11.10 and Figure 11.11). The highest value is on top surface but in the quantitative comparison with the strengths is considered also the maximum tension at bottom surface in LC3 due to its concentration and intensity. Figure 11.12, Figure 11.13 and Figure 11.14 show the location of the maximum stresses for every load case and the points that are considered as critical. In the same figures are shown also the principal directions. In the Table 11.2, Table 11.3 and Table 11.4 the stresses in the critical points are compared with the related strengths of the plywood defined according the APA (The Engineered Wood Association, 1997) specifications.

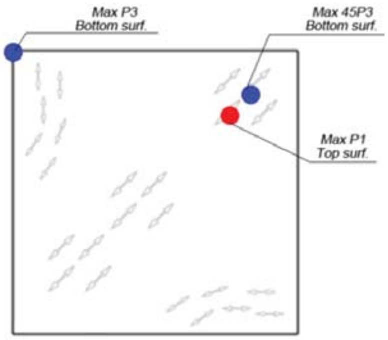


Figure 11.12 – Principal directions and location of maximum stresses LC1

Table 11.2 - Comparison stresses/strength LC1

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-4,44	-6,83	**0,65**
Max 45P3	**Fc/3**	**3P3/Fc**
-2,00	-2,28	**0,88**
Max P1	**Ft/6**	**6P1/Ft**
1,94	1,38	**1,41**

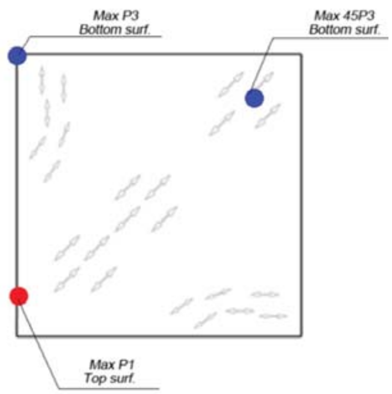


Figure 11.13 – Principal directions and location of maximum stresses LC2

Table 11.3- Comparison stresses/strength LC2

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,3	-6,83	**0,34**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,00	-2,28	**0,44**
Max P1	**Ft/6**	**6P1/Ft**
1,22	1,38	**0,89**

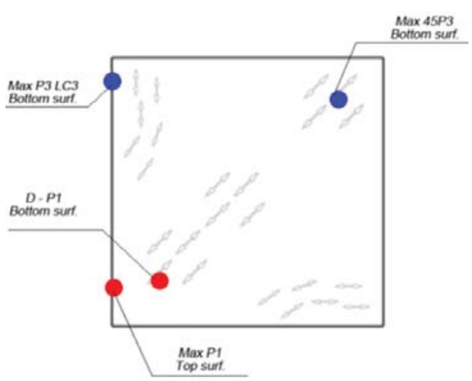


Figure 11.14– Principal directions and location of maximum stresses LC3

Table 11.4 - Comparison stresses/strength LC3

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,52	-6,83	**0,37**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,08	-2,28	**0,47**
Max P1	**Ft/6**	**6P1/Ft**
1,93	1,38	**1,4**
D-P1	**Ft/6**	**6D/Ft**
1,08	1,38	**0,78**

In all the three load cases the compression does not lead to any critical situation as the maximum stresses are lower than the strengths. The comparison with the strength underlines that the tensile strength is exceeded in the LC1 and LC3 and the ratio stress/strength is almost the same in the two load cases. What differentiates them is the localization of this stresses.

In LC1 the highest tensile strength is in the corner between the two tilted edges (A in Figure 11.9) but is spread along a larger area than in the case of LC3. In third load case the maximum tensile stress is extremely localized in the horizontal edges close to the corner between them (C in Figure 11.11).
From the fact that the allowable stress in tension is exceeded and that the tensile stresses are extremely localized in a small area make possible to deduce that the load case LC3 is the most critical.
The vertical displacement of the diagonal of the structures that goes from the corner of the horizontal edges to the corner of the free edges highlights that LC1 leads to the larges deflection.

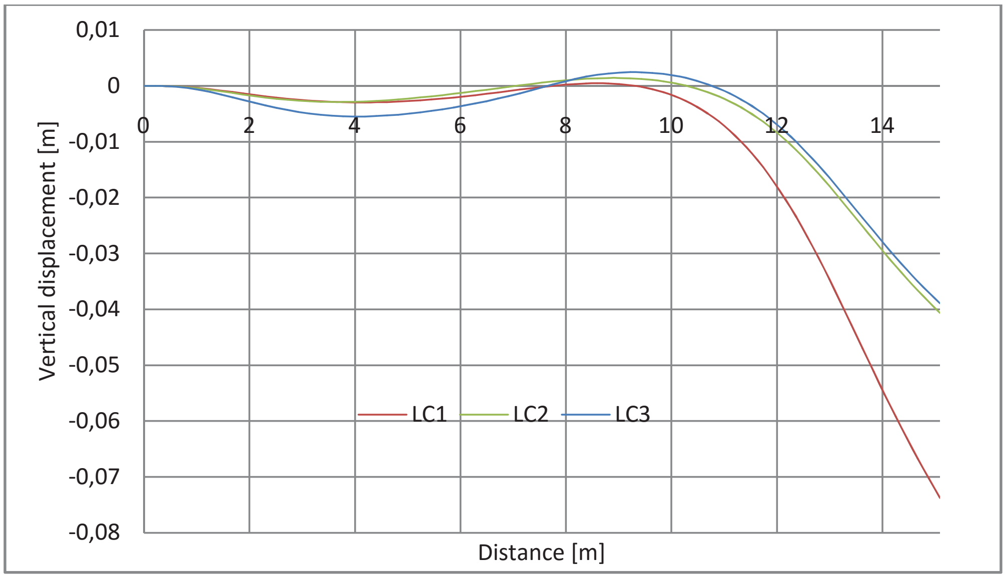


Figure 11.15 - Vertical displacement of the diagonal

LC4-LC5

Following the same methodology of comparison of the results showed in the previous case of the snow load, the maximum principal stresses in the mid surface are computed and shown in the Table 11.5 for the both snow load cases.

Table 11.5 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% difference between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC4	Max	-0,71	0,17	76	0	0
	Min	0	0			
LC5	Max	-3,48	1,02	71	389	496
	Min	0	0			

The table above highlights immediately the big difference between the maximum principal stresses induced by the LC4 and LC5. This is due to the fact that the LC4 has a low intensity. Their difference can be observed also in the band plot of the stresses. They have the same scale and is defined by the fifth load case as it present the highest values of stresses.

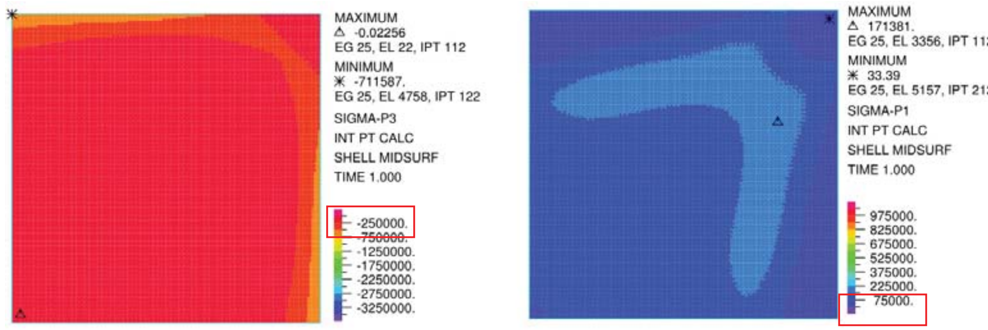


Figure 11.16 – LC4 (P3 left, P1 right) Midsurface [Pa]

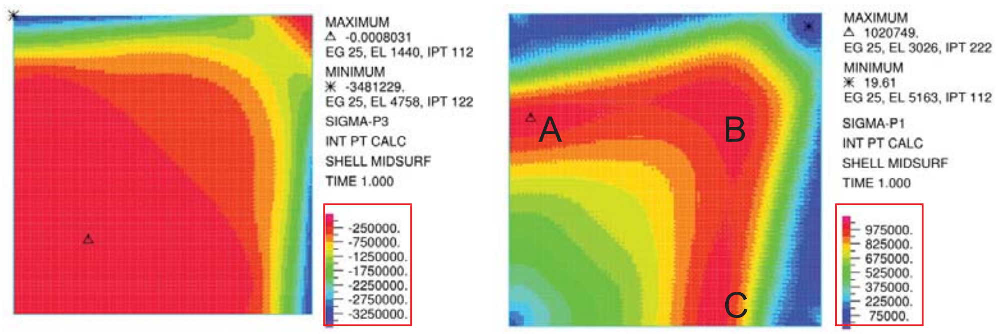


Figure 11.17 – LC5 (P3 left, P1 right) Midsurface [Pa]

The mid surface band plots show how the range of principal stresses is small in the LC4 compared with LC5. The LC5 distributes the compression stresses mainly in half area of the structure, where the load is acting, with a higher concentration in the tilted edges close to the supports. Concerning the tension, it is mainly distributed in two areas, perpendicular to the horizontal edge beams, and with a higher concentration in three areas indicated with A,B and C in the Figure 11.17.

The distribution of the stresses along the thickness (top and bottom surface) for both load cases are shown in the Figure 11.18 and Figure 11.19.

From these last band plots is possible to conclude that concerning the compression the behavior of the structure under the two load is similar; on top surface the maximum compression is concentrated in the tilted edges (point A in Figure 11.18 and Figure 11.19) , while in the bottom surface is concentrated in the support (point B in Figure 11.18 and Figure 11.19).

The main difference between the two load cases is in tension behavior. In the fourth load case the tension is concentrated in two areas (C and D in the Figure 11.18). The tension (D in Figure 11.18) in the tilted edges close to the free corner is a consequence of the fact that here the final load is almost tangent to the surface and this is reflected in tension in the edge connection.

In the LC5, the concentration of tensile behavior at the top surface is in the same area as previously (C in Figure 11.19), while at the bottom surface the wind downward in half area of the shell (in the side of the tilted edge beams) induces to high concentration of tensile stresses (P1) in the horizontal edges (area indicated by E in the Figure 11.19).

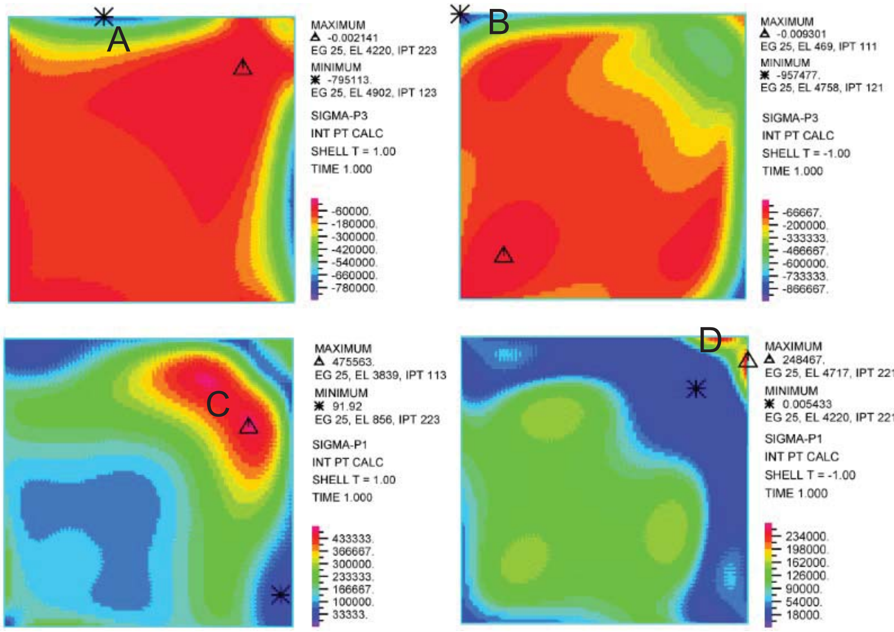


Figure 11.18 – LC4: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

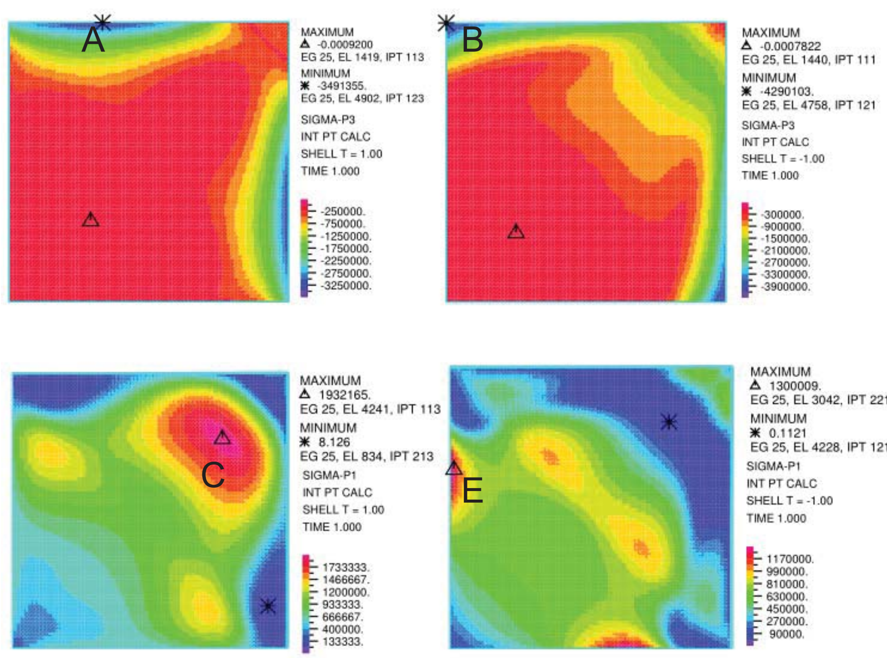


Figure 11.19 – LC5: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

The maximum principal stresses in compression and tension (P3 and P1) are compared with the allowable stresses (Table 11.6 and Table 11.7) taking always into account the principal direction (Figure 11.20 and Figure 11.21).

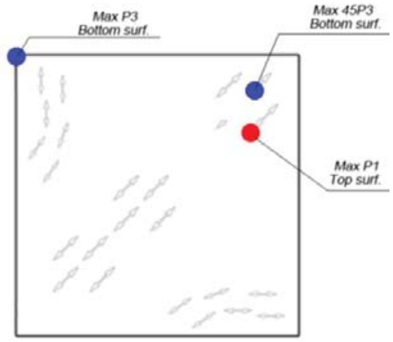


Figure 11.20 – Principal directions and location of maximum stresses LC4

Table 11.6 - Comparison stresses/strength LC4

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-0,96	-6,83	**0,14**
Max 45P3	**Fc/3**	**3P3/Fc**
-0,47	-2,28	**0,21**
Max P1	**Ft/6**	**6P1/Ft**
0,48	1,38	**0,35**

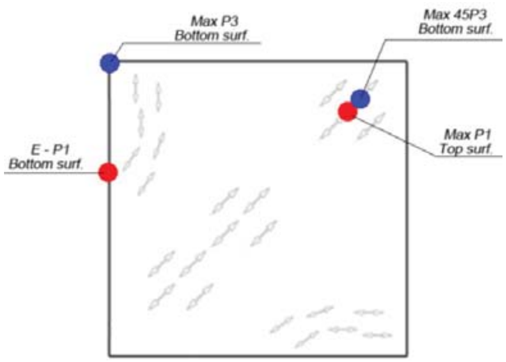


Figure 11.21– Principal directions and location of maximum stresses LC5

Table 11.7 - Comparison stresses/strength LC5

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-4,29	-6,83	**0,63**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,80	-2,28	**0,79**
Max P1	**Ft/6**	**6P1/Ft**
1,93	1,38	**1,4**
E-P1	**Ft/6**	**6D/Ft**
1,3	1,38	**0,94**

The quantitative comparison shows that fourth load case does not induce to critical situations for both compression and tension behavior. The fifth load case is characterized by an exceedance of the allowable stress in tension. The stress exceeds the strength of about 40% in the area indicated by C in the (Figure 11.19). Moreover, a critic situation is also on the bottom surface in the area E indicated in Figure 11.19, since here the stress is similar to the strength (the ratio stress/strength is 0,94) and is highly localized in the horizontal edges.

The high difference in term of stresses between the two load cases is also confirmed by the graph (Figure 11.22) that shows the vertical displacement of the diagonal that is on the symmetric axis. In the LC4 the maximum displacement is around 1 cm while in the second load case is 7,4 cm.

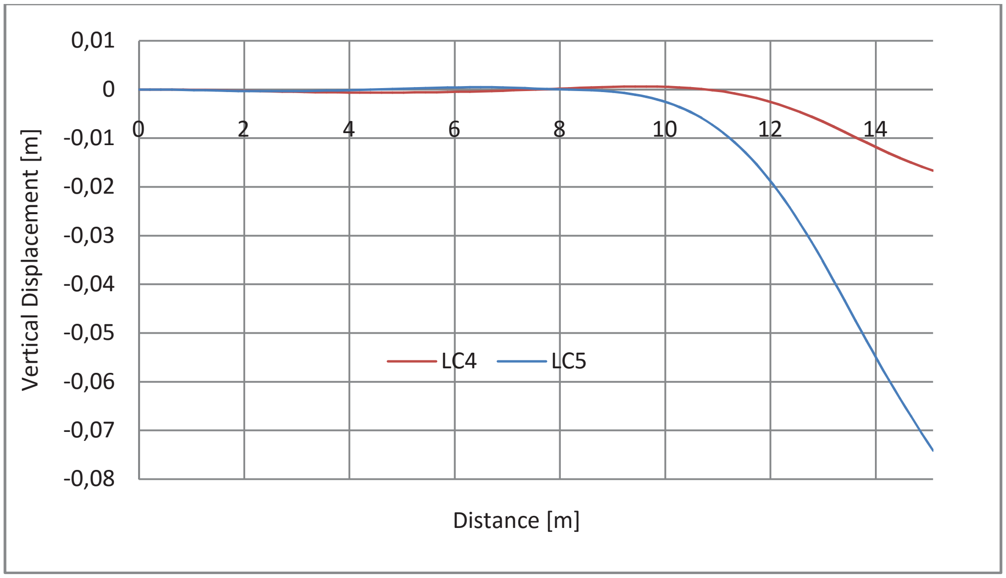


Figure 11.22 - Vertical displacement of the diagonal

11.3.2 Second Configuration - 2nd

LC1-LC2-LC3

The same method defined in the comparison of the previous results, concerning the clamped edge as boundary conditions, is used for the comparison where the horizontal edges are hinged. The maximum principal stresses in the mid surface are shown in the Table 11.8.

Table 11.8 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% differentce between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC1	Max	-4,31	1,03	76	20	2
	Min	0	0			
LC2	Max	-2,21	0,59	73	-49	-43
	Min	0	0			
LC3	Max	-2,27	0,91	60	-47	-12
	Min	0	0			

As in the case of clamped edges, the LC1 induces the highest stresses in the structure and it present the highest percentage of difference between P3 and P1. The Table 11.9 compares the maximum stresses in the case of clamped edges (1st Configuration) with the ones considering the edges hinged. The values are not differing significantly but the configuration with hinged edges is presenting higher values, except for the stresses P1 in LC2 and LC3.

Table 11.9 - Comparison of maximum stresses on mid surface between 1st and 2nd configurations

		1st Configuration Clamped Edges		2nd Configuration Hinged edges			
		P3C [MPa]	P1C [MPa]	P3H [MPa]	P1H [MPa]	P3C/P3H	P1C/P1H
LC1	Max	-3,60	1,02	-4,31	1,03	**0,83**	**0,98**
	Min	0	0	0	0		
LC2	Max	-1,80	0,60	-2,21	0,59	**0,81**	**1,01**
	Min	0	0	0	0		
LC3	Max	-1,87	0,92	-2,27	0,91	**0,82**	**1,01**
	Min	0	0	0	0		

Figure 11.23, Figure 11.24 and Figure 11.25 show the distribution of the principal stresses, in the mid surface, for the three load cases. All the band plot have the same range and is defined from the LC1 that present the highest values.

The band plot of the principal stresses in the mid surface, show almost the same trend of behavior as in the case of clamped edges. The mainly difference is that the compression in the LC3 is more homogeneous than the case with clamped edges and this is mainly due to the deformed shape. Still the maximum values of compression interest corners between the horizontal and tilted edges. The tension is getting more localized, as in the previous case, in the corner between the two horizontal edge beams but with lower magnitude than the case of clamped edges.

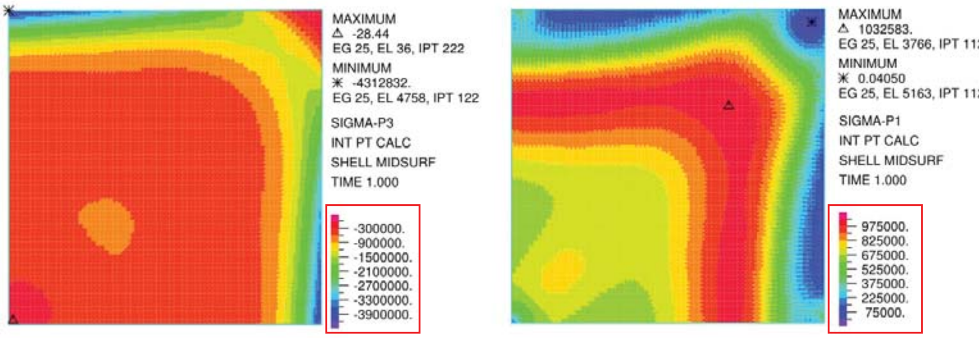


Figure 11.23 - LC1 (P3 left, P1 right) Midsurface [Pa]

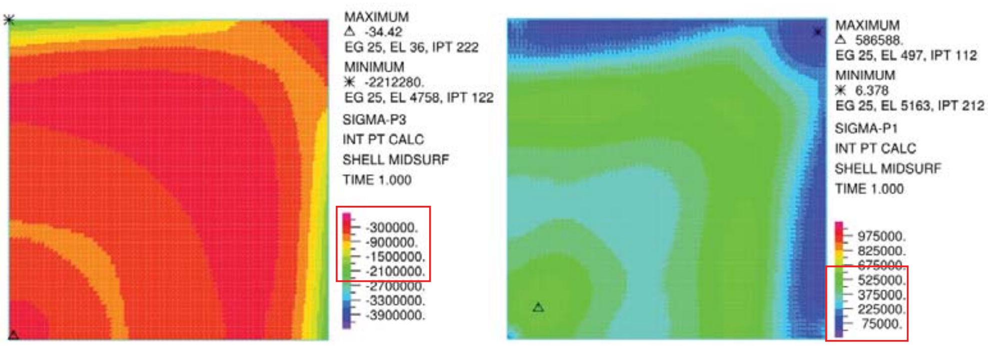


Figure 11.24 - LC2 (P3 left, P1 right) Midsurface [Pa]

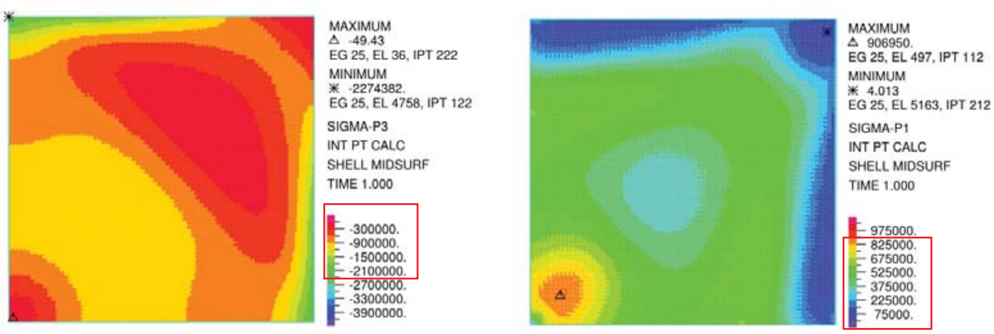


Figure 11.25 - LC3 (P3 left, P1 right) Midsurface [Pa]

In addition to the stresses in the mid surface, also the stresses in the top and bottom surface are processed (Figure 11.28, Figure 11.29 and Figure 11.30). The maximum compression is always in the supports that connects the horizontal edges with the tilted as in the previous case. The most important difference concern the concentration of the tensile stresses in the load case LC3. In the previous case the tensile stress P1 on top surface was concentrated in the horizontal edges close to the support, while in this case the concentration of tensile stresses is not along the edges but in the support between the two horizontal edges (A in Figure 11.30). The Figure 11.26 and Figure 11.27 shows the difference in the two cases.

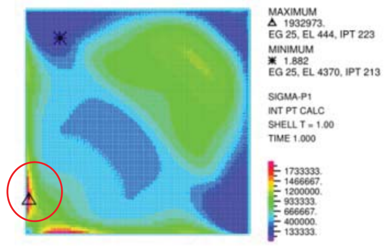


Figure 11.26 – 1st Configuration LC3- P1 Top

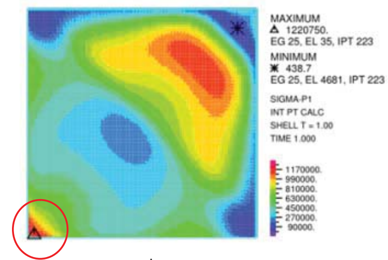


Figure 11.27 – 2nd Configuration LC3- P1 Top

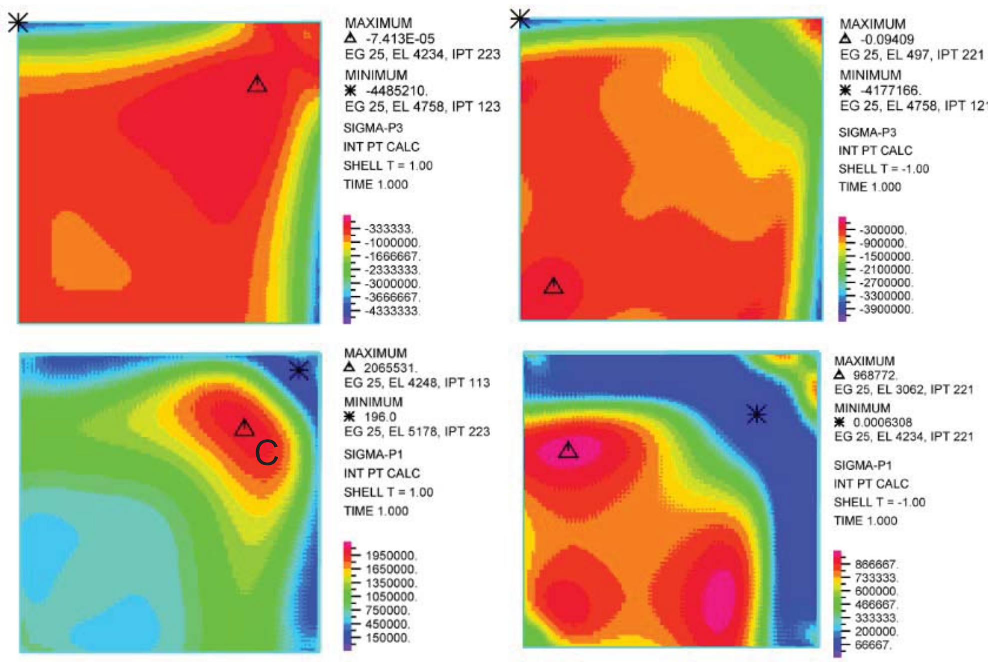


Figure 11.28 - LC1: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

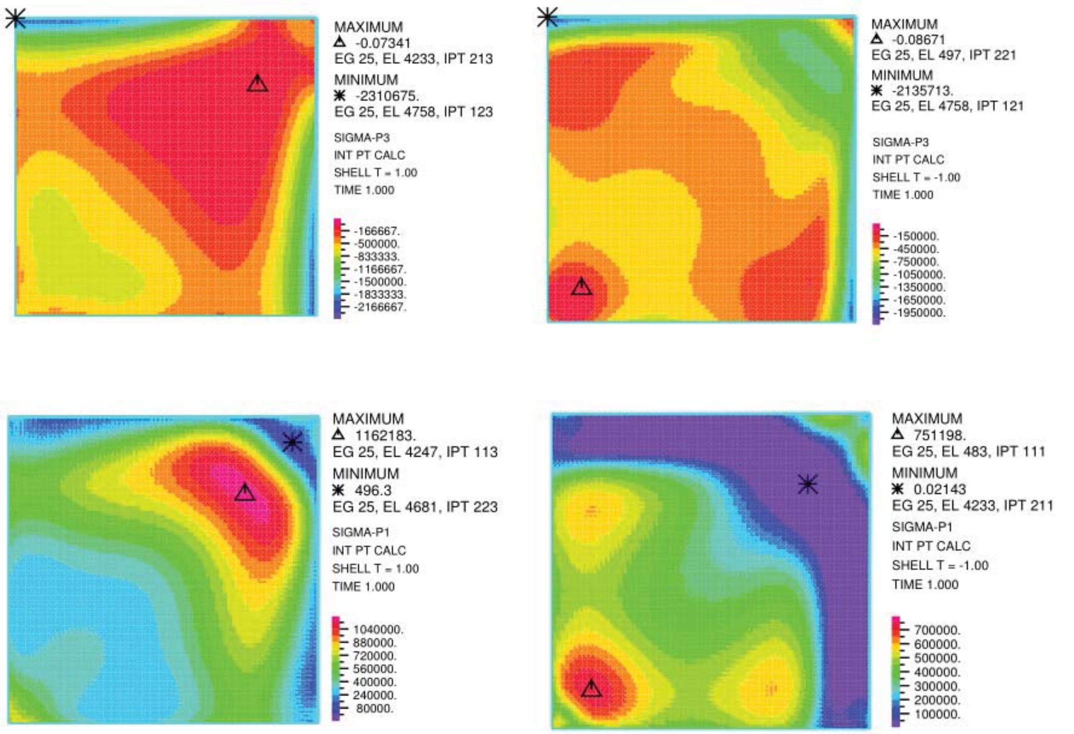


Figure 11.29 – LC2: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

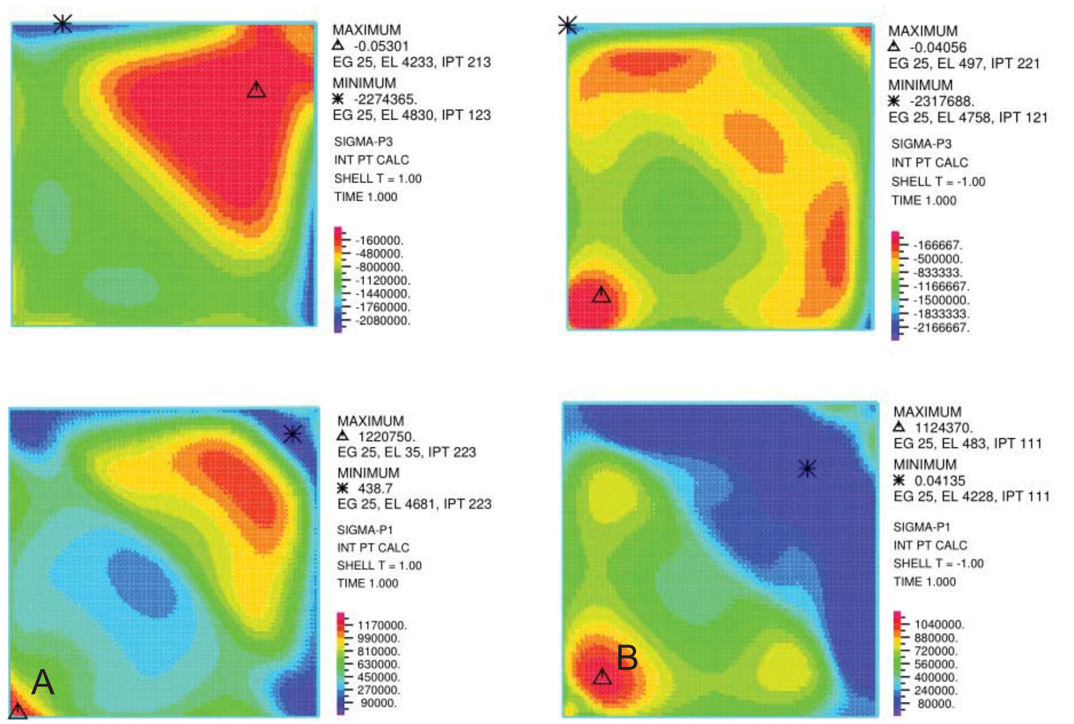


Figure 11.30 - LC3: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

The qualitative analysis shows that the behavior is not changing significantly passing from clamped edges to hinged. As in the previous case the maximum stresses, compression and tension, are compared with the allowable stresses, relating always the stress with its principal direction. Figure 11.31, Figure 11.32 and Figure 11.33 shows the location of the principal stresses and the scheme of the principal directions, which is not changing significantly from the previous case.

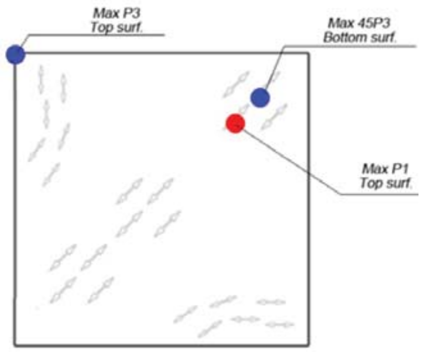


Figure 11.31– Principal directions and location of maximum stresses LC5

Table 11.10 - Comparison stresses/strength LC1

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-4,49	-6,83	**0,65**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,80	-2,28	**0,79**
Max P1	**Ft/6**	**6P1/Ft**
2,06	1,38	**1,5**

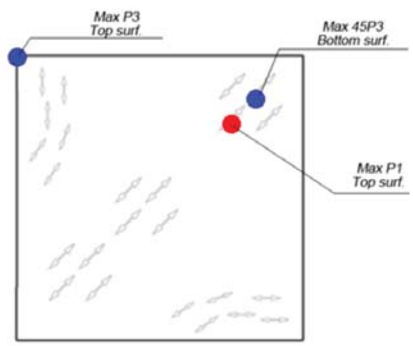


Figure 11.32– Principal directions and location of maximum stresses LC5

Table 11.11 - Comparison stresses/strength LC2

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,31	-6,83	**0,34**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,50	-2,28	**0,66**
Max P1	**Ft/6**	**6P1/Ft**
1,16	1,38	**0,84**

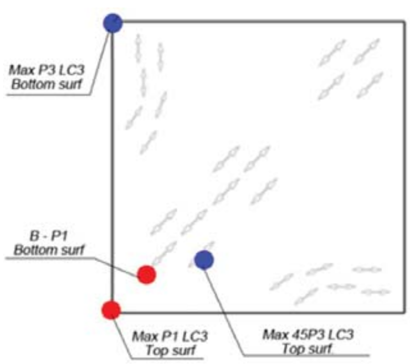


Figure 11.33 – Principal directions and location of maximum stresses LC5

Table 11.12 - Comparison stresses/strength LC3

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,32	-6,83	**0,34**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,60	-2,28	**0,7**
Max P1	**Ft/6**	**6P1/Ft**
1,22	1,38	**0,88**
B-P1	**Ft/6**	**6D/Ft**
1,12	1,38	**0,81**

Figure 11.31, Figure 11.32 and Figure 11.33 underline that in the first two load cases the maximum stresses coincide in the same location and surface. Moving from those two load cases to the third the behavior is changing as the maximum concerning the compression P3 is remaining in the same corner but is moving in the bottom surface. The maximum tensile stress is moving in the opposite corner of the load cases LC1 and LC2 and with a higher concentration in the support.

In Table 11.10, Table 11.11 and Table 11.12 the maximum stresses are compared with the allowable stresses. The ratios stress/strength evidence that the most critical load case is the LC1, with a special regard to the tensile stress that exceeds the strength by 50%. Comparing with the previous configuration, the ratios stress/strength are getting lower in the load cases 2 and 3, especially in the last one, that previously was the most critical.

Summarizing in the configuration with hinged horizontal edges the most critical load case is the first were the snow is uniformly distributed all over the surface. The criticality concern the tensile stress and is localized in the corner between the two tilted edges (C in Figure 11.28).

Changing from clamped edges (1^{st} Configuration) to hinged edges (2^{nd} Configuration) is not affected significantly the displacement, as is possible to notice in the Figure 11.34.

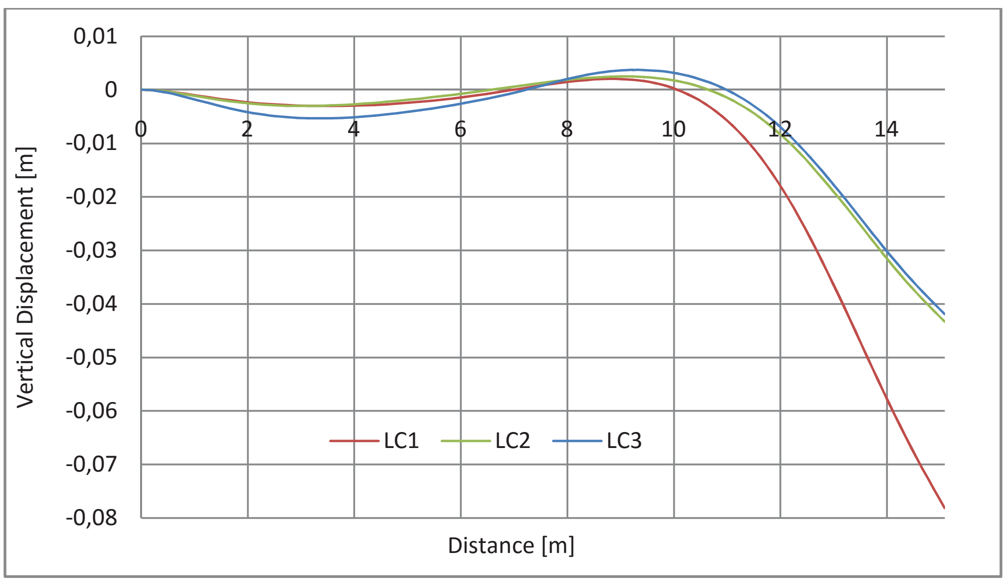


Figure 11.34 – Vertical displacement of the diagonal

LC4-LC5

Considering the horizontal edges as hinged the principal stresses in the mid surface increase (Table 11.14) compared with the clamped edges (1^{st} Configuration). However, in LC4 they still remain quite low (Table 11.13) due to the small intensity of the final pressure.

Table 11.13 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% difference between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC4	Max	-0,93	0,19	79	0	0
	Min	0	0			
LC5	Max	-4,22	1,10	74	352	469
	Min	0	0			

Table 11.14 - Comparison of maximum stresses on mid surface between 1st and 2nd configurations

		1st Configuration Clamped Edges		2nd Configuration Hinged edges			
		P3C [MPa]	P1C [MPa]	P3H [MPa]	P1H [MPa]	P3C/P3H	P1C/P1H
LC4	Max	-0,71	0,17	-0,93	0,19	0,76	0,88
	Min	0	0	0	0		
LC5	Max	-3,48	1,02	-4,22	1,10	0,83	0,92
	Min	0	0	0	0		

Concerning the fifth load case, the principal stresses increase of around 17% in compression and 8% in tension, respect the case where the edges were clamped. The band plots (Figure 11.35 and Figure 11.36) show the low influence of the LC4 in comparison with the LC5 (the band plots are referred to the same range defined from the LC5 since has the highest values). In LC5 the behavior in the mid surface is similar to the previous case with clamped edges. The main difference is regarding the principal tension P1 that is distributed in a similar way, but in this case the concentration in three main areas (A,B and C in Figure 11.36) is more evident.

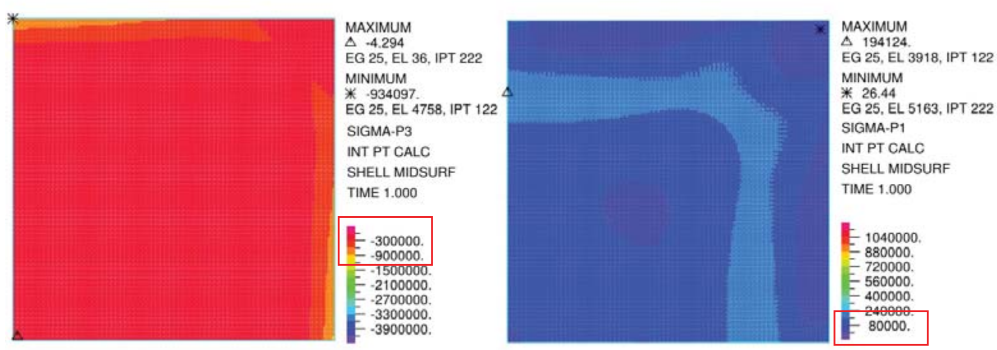


Figure 11.35 - LC4 (P3 left, P1 right) Midsurface [Pa]

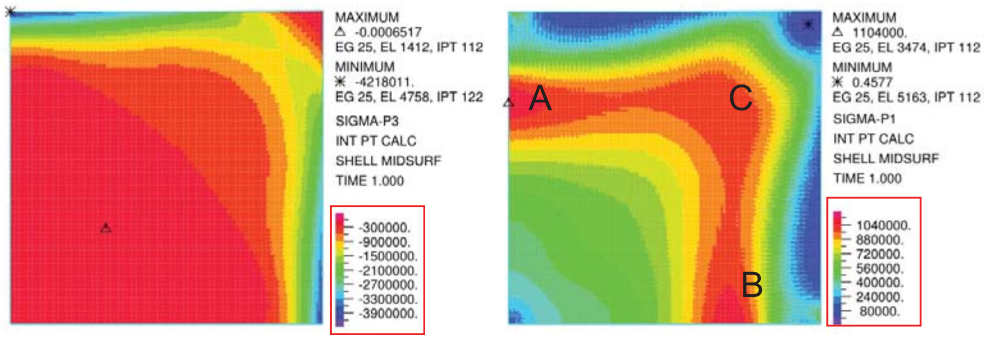


Figure 11.36 – LC5 (P3 left, P1 right) Midsurface [Pa]

From the band plots through the thickness (top and bottom, Figure 11.37 and Figure 11.38) is possible to notice that in the case of hinged edges the behavior of the structure does not change significantly respect the case of the clamped edges.

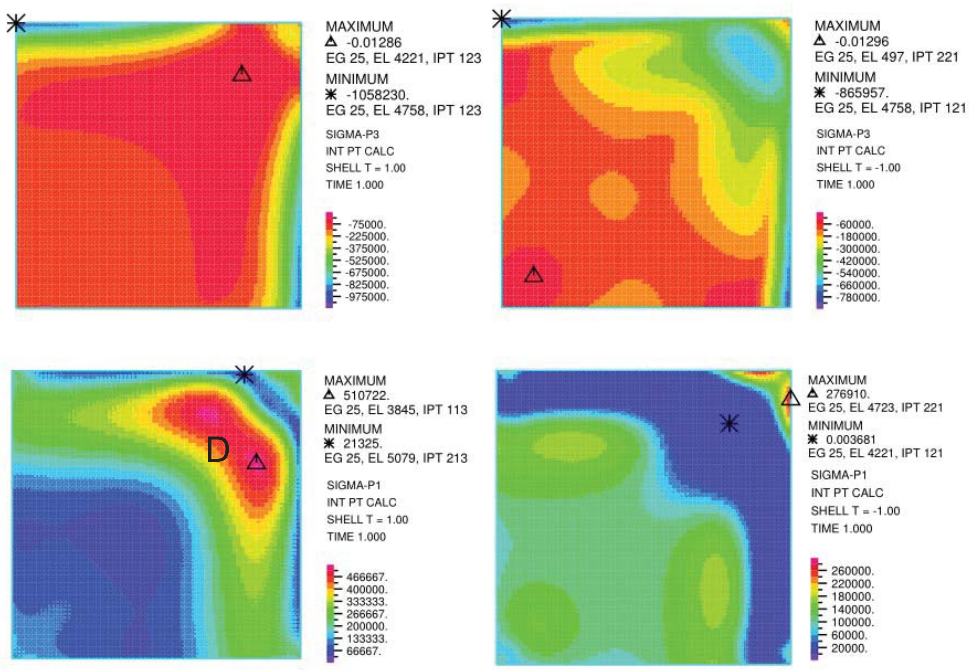


Figure 11.37 – LC4: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

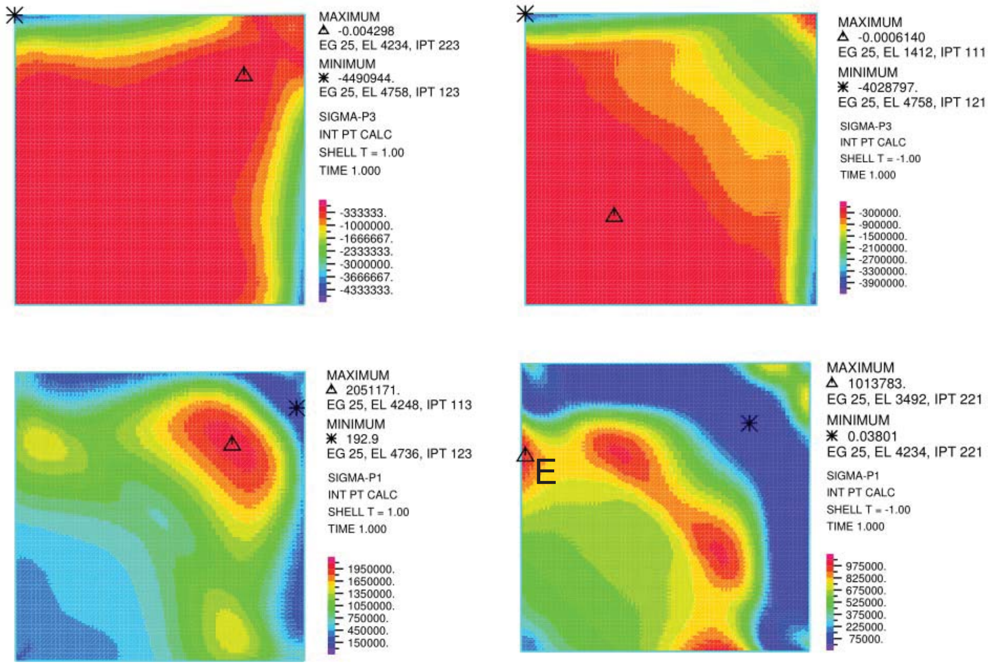


Figure 11.38 – LC5: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

The maximum values of principal stresses are almost in the same areas as in the previous configuration. Compression is, in both load cases, concentrated in the supports between tilted and horizontal edges. The difference between the two load cases, in tension behavior, regards the bottom surface; in the fourth load case is concentrated in the tilted edges close to their shared corner (D in Figure 11.37), while in the fifth load case is concentrated in the horizontal edge beam (E in Figure 11.38). Table 11.15 and Table 11.16 compare the maximum principal stresses with the allowable stresses depending on the principal directions (Figure 11.39 and Figure 11.40). In the quantitative comparison is considered also the principal tensile stress in the bottom surface of the fifth load case because is highly concentrated and present a high value.

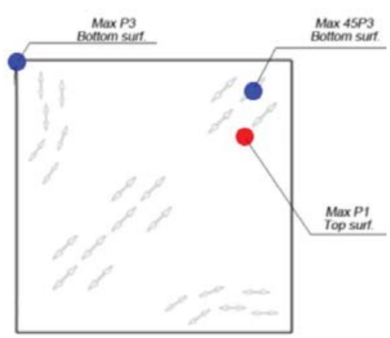


Figure 11.39 – Principal directions and location of maximum stresses LC4

Table 11.15 - Comparison stresses/strength LC4

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-1,06	-6,83	**0,15**
Max 45P3	**Fc/3**	**3P3/Fc**
-0,42	-2,28	**0,18**
Max P1	**Ft/6**	**6P1/Ft**
0,51	1,38	**0,37**

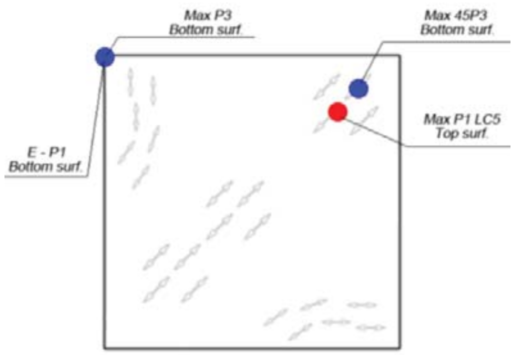


Figure 11.40 – Principal directions and location of maximum stresses LC5

Table 11.16 - Comparison stresses/strength LC5

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-4,49	-6,83	**0,66**
Max 45P3	**Fc/3**	**3P3/Fc**
-2,10	-2,28	**0,92**
Max P1	**Ft/6**	**6P1/Ft**
2,05	1,38	**1,48**
E-P1	**Ft/6**	**6D/Ft**
1,01	1,38	**0,73**

The quantitative and qualitative comparison of the results concerning the load case evidence that passing from clamped to hinged edges the principal stresses increases, but the structural response of the structure remains almost the same. The distribution of stresses and the localization of the maximum values are similar to the previous case. The most critical situation is due to the fifth load case since the tensile strength behavior is exceeded of about 50% in the area close to the corner between the tilted edges. The point E, in the configuration with clamped edges, was characterized by a ratio of 0,94 highlighting its critical situation, while in this case the ratio decreases (0,73), meaning that the only critic situation is the one mentioned before where the tensile strength is exceeded of about 50%.

The Figure 11.41 compares the two wind load cases in terms of displacement of the diagonal that connects the corner between the horizontal edges with the opposite one. The comparison confirms the high difference of the two load cases.

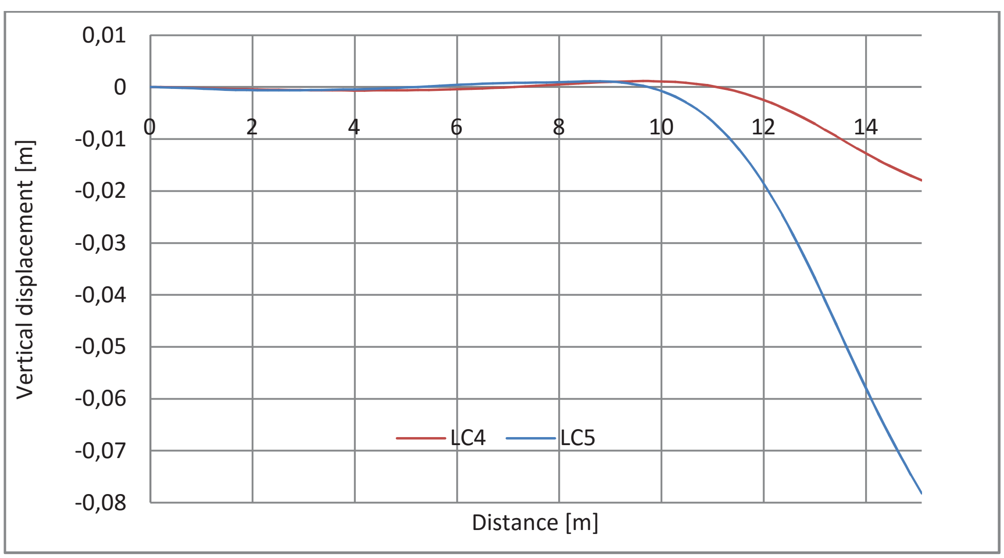


Figure 11.41 - Vertical displacement of the diagonal

11.3.3 Third Configuration - 3rd

LC1-LC2-LC3

From the linear elastic analysis the maximum principal stresses, in the mid surface, are computed and shown in the following table.

Table 11.17 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% difference between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC1	Max	-2,41	0,82	66	0	0
	Min	0	0			
LC2	Max	-1,13	0,57	49	-53	-30
	Min	0	0			
LC3	Max	-1,27	0,90	29	-47	10
	Min	0	0			

The Table 11.17 underlines that the LC1 induces the highest compressive stress in the mid surface, while the LC3 the highest tensile stress. Moving from the LC1 to LC3 the difference between the tensile and compressive principal stresses (P3 and P1) is getting lower, which is reflected in a more homogeneous distribution of the maximum stresses.

Comparing the maximum stresses in the mid surface for this configuration with the configuration where posts are not taken into account the values are lower in a significant way, especially concerning the compression values (P3)Table 11.18.

Table 11.18 - Comparison of maximum stresses on mid surface between 1st and 3rd configurations

		1st Configuration No Posts - Clamped Edges		3rd Configuration Yes Posts - Clamped edges			
		P3C [MPa]	P1C [MPa]	P3H [MPa]	P1H [MPa]	P3C/P3H	P1C/P1H
LC1	Max	-3,60	1,02	-2,41	0,82	**1,49**	**1,25**
	Min	0	0	0	0		
LC2	Max	-1,80	0,60	-1,13	0,57	**1,59**	**1,04**
	Min	0	0	0	0		
LC3	Max	-1,87	0,92	-1,27	0,90	**1,47**	**1,02**
	Min	0	0	0	0		

The localization of the maximum stresses in the mid surface is shown in Figure 11.42, Figure 11.43 and Figure 11.44.

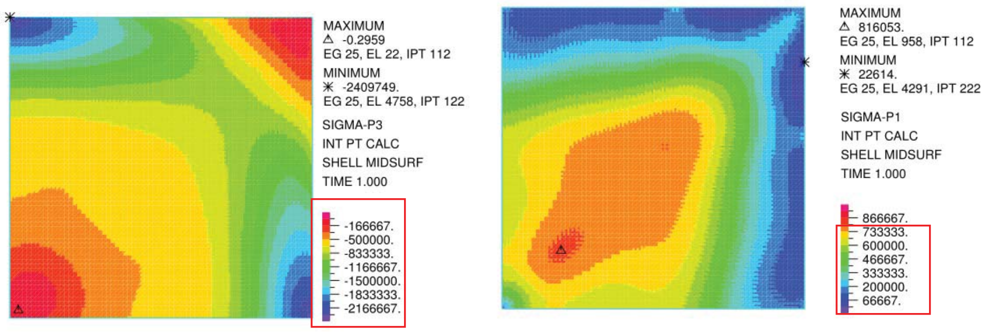


Figure 11.42 - LC1 (P3 left, P1 right) Midsurface [Pa]

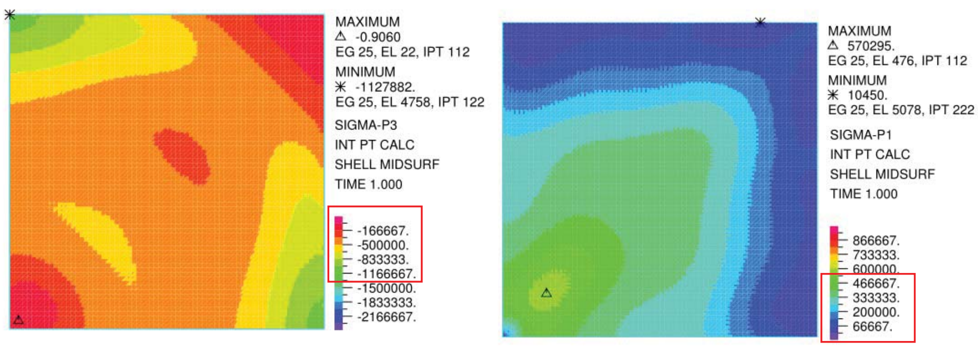


Figure 11.43 – LC2 (P3 left, P1 right) Midsurface [Pa]

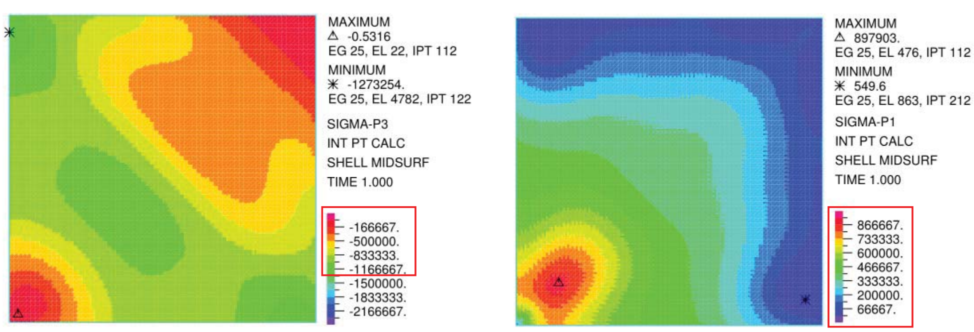


Figure 11.44 – LC3 (P3 left, P1 right) Midsurface [Pa]

From the band plots is possible to notice that the maximum values are almost in the same areas in all the load cases, meanwhile in the previous cases the maximum tension in the mid surface of LC1 was located in the corner between the two tilted edges. Moreover, always regarding the LC1, in this configuration the compression in the mid surface is extended also in the central area of the shell structure. Also the behavior on tension is changing as in this case is not perpendicular to the horizontal edges but is more distributed along the diagonal the connects the two corners from the horizontal edges to the tilted edges. Moving from LC1 to LC3 the tension is getting more localized in the corner between the horizontal edges and also the compression is moving from the area between the tilted edges to the area between the horizontal ones.

A wider view of the behavior of the structure is obtained by plotting the stresses not only in the mid surface but also on the top and bottom surface (Figure 11.45, Figure 11.46 and Figure 11.47).

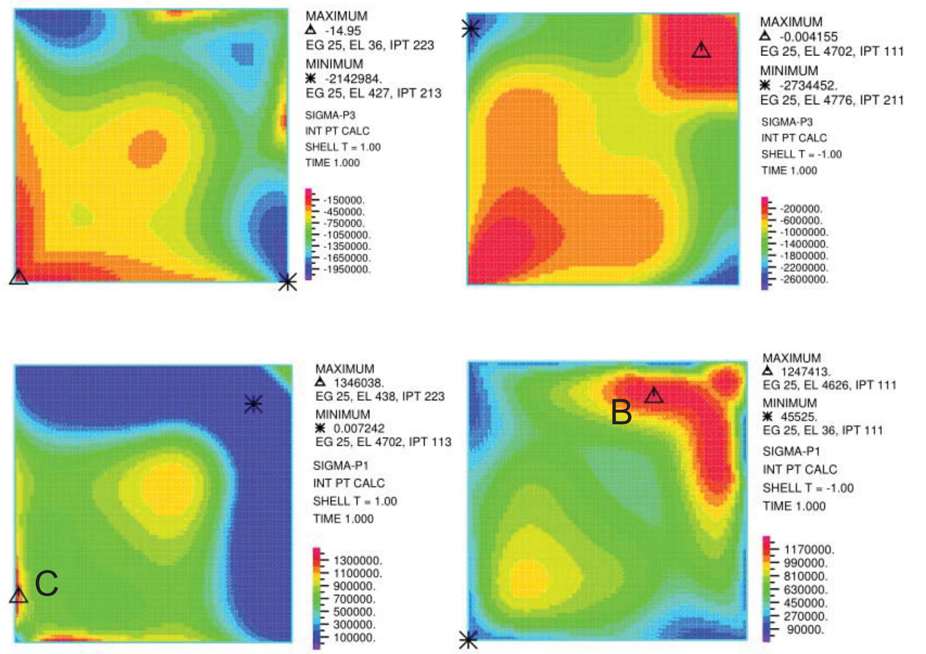


Figure 11.45 – LC1: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

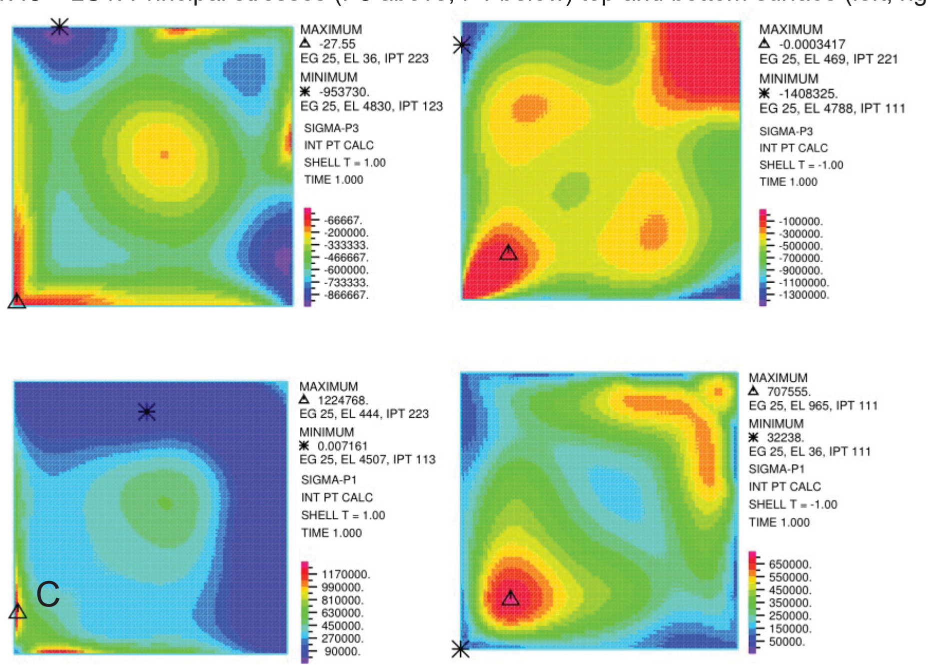


Figure 11.46 – LC2: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

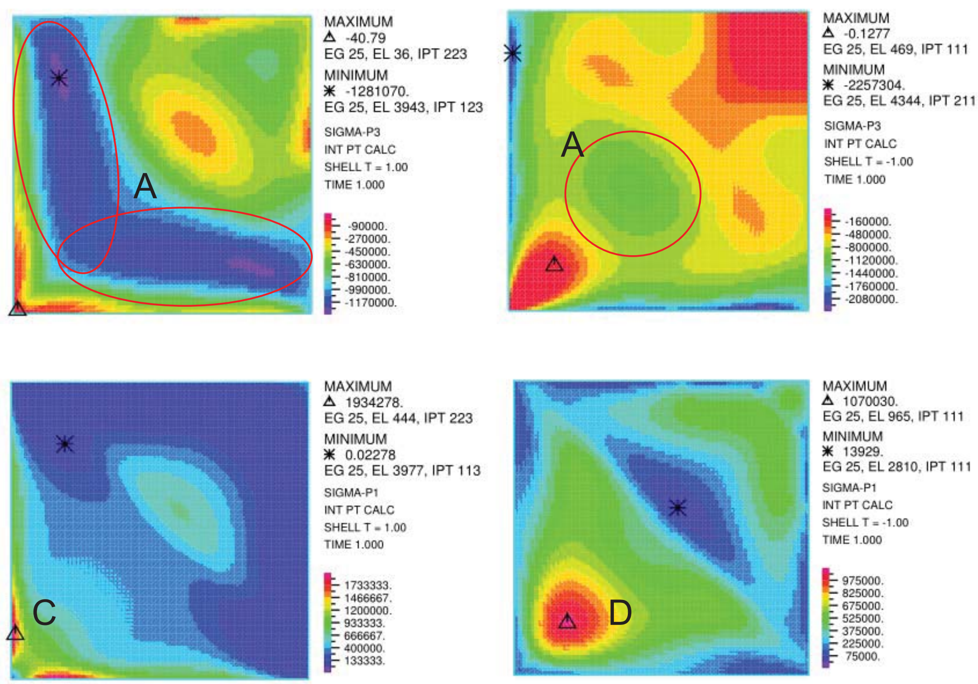


Figure 11.47 - LC3: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

The figures above underlines that the addition of the posts as structural elements changes the behavior of the structure both in compression and tension.

Concerning the compression, in this configuration, it is not concentrated mainly in the supports but its high intensity distribution is getting wider in the central area of the shell, where the principal directions are at 45° and the strength is divided by three. This wider distribution is clearly highlighted in the third load case on the top surface (indicated by A in Figure 11.47).

Regarding the tension behavior in LC1 there are two main areas with the highest localization of the tensile behavior. The first is localized in the corner between the two tilted edges (indicated by B in Figure 11.45), while the second area is in the horizontal edges close to the support between them (indicated by C in Figure 11.45). Moving from LC1 to LC2 and LC3 the difference between tensile stresses in the areas indicated by B and C is increasing and getting higher in the last one as the load is increasing. Indeed, the highest value of tensile stress P1 is located in this area and concern the third load case.

From this qualitative comparison is possible to say that in LC1 two main areas of the shell are subjected to high concentration of tensile stresses. Moving forward in the following load cases, LC2 and LC3, the concentration is mainly affecting only the corner between the horizontal edges.

Moreover the weakness in the horizontal edges close to the support (indicated by C in the Figure 11.45) is shown immediately from the first Load case. In the first configuration (clamped edges and no posts) this weakness was coming out clearly only in the third load case.

Figure 11.48, Figure 11.49 and Figure 11.50 shows the stresses considered in the quantitative comparison and the related principal directions. These values are compared with the allowable stresses in Table 11.19, Table 11.20 and Table 11.21.

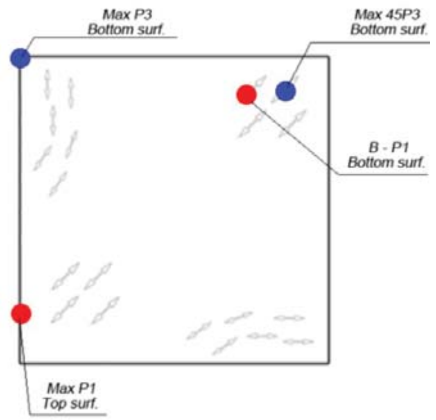


Figure 11.48 – Principal directions and location of maximum stresses LC1

Table 11.19 - Comparison stresses/strength LC1

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,73	-6,83	**0,40**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,80	-2,28	**0,79**
Max P1	**Ft/6**	**6P1/Ft**
1,35	1,38	**0,98**
B-P1	**Ft/6**	**6D/Ft**
1,25	1,38	**0,90**

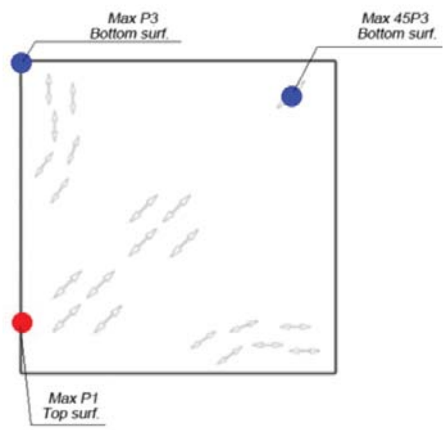


Figure 11.49 – Principal directions and location of maximum stresses LC2

Table 11.20 - Comparison stresses/strength LC2

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-1,41	-6,83	**0,21**
Max 45P3	**Fc/3**	**3P3/Fc**
-0,80	-2,28	**0,35**
Max P1	**Ft/6**	**6P1/Ft**
1,22	1,38	**0,89**

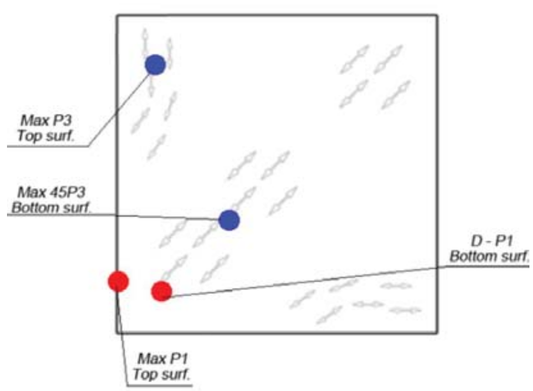


Figure 11.50 – Principal directions and location of maximum stresses LC3

Table 11.21 - Comparison stresses/strength LC3

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-1,28	-6,83	**0,19**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,28	-2,28	**0,56**
Max P1	**Ft/6**	**6P1/Ft**
1,93	1,38	**1,4**
D-P1	**Ft/6**	**6D/Ft**
1,07	1,38	**0,77**

Concerning the compression the ratios stress/strength are the lowest between all the configurations analyzed until now and this underlines that P3 does not induce in critical situation in all the three load cases.

Regarding P1, the second load case has the lowest ratio stress/strength indicating that this load case does not represent a critic situation. In the first load case is close to the limit as its ratio is 0,98. Moreover, as explained before, this load case has also another area where the high value of tension is concentrated (point B in the Figure 11.45: 1247 [kPa]) and the related ratio stress strength is 0,90. In the third load case the strength is even exceeded by the stress and it is strongly localized in a small area accentuating the dangerous situation (C in Figure 11.47).

In terms of displacement (Figure 11.51) the configuration where the post are structurally considered is inducing to lower deflection values. The LC1 concentrates the highest deflection in the area close to the corner between the tilted edges, and the value is 1,7 cm. With the adding of the snow load in the opposite area (LC2 and LC3) the deflection is getting more uniform between the two areas. The changing of curvature of the deflection graph at around 8 meters is mainly due to the presence of the two lateral posts. In these posts is also the reason to why in the LC1 there are two areas where the tensile stress has high values.

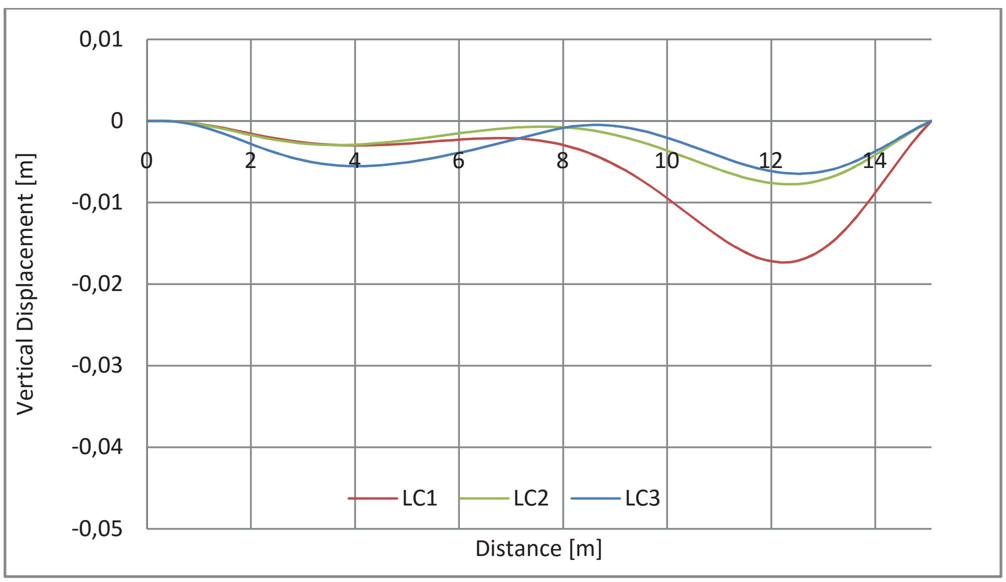


Figure 11.51 – Vertical Displacement of the diagonal

LC4-LC5

The introduction of the posts as structural elements is reducing the maximum stresses also in the case of the wind load. The Table 11.22 summarizes the maximum principal stresses in the mid surface and those stresses are also compared (in the Table 11.23) with the configuration where the edges are clamped and the posts are not considered.

Table 11.22 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% differentce between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC4	Max	-0,43	0,13	70	0	0
	Min	0	0			
LC5	Max	-2,32	0,83	64	437	549
	Min	0	0			

Table 11.23 - Comparison of maximum stresses on mid surface between 1st and 3rd configurations

		1st Configuration		3rd Configuration			
		P3C [MPa]	P1C [MPa]	P3H [MPa]	P1H [MPa]	P3C/P3H	P1C/P1H
LC4	Max	-0,71	0,17	-0,43	0,13	**1,65**	**1,33**
	Min	0	0	0	0		
LC5	Max	-3,48	1,02	-2,32	0,83	**1,50**	**1,22**
	Min	0	0	0	0		

The comparison in the Table 11.23 shows that the addition of the posts is reducing both, tensile and compressive, principal stresses and in a significant way the second ones. The band plots of the principal stresses in the mid surface (Figure 11.52 and Figure 11.53) point out the high difference between the stresses induced by the fourth and fifth load case. The stresses of the fourth load case are much more lower (as already shown in Table 11.22) than the fifth.

In terms of stress distribution in the mid surface the main difference between the two load cases is in tension, since the compression in both load cases is concentrated in the supports between tilted and horizontal edges. The difference in tension is that in the fourth load case is more concentrated in the corner between the horizontal edges (indicated by A in the Figure 11.52), while the fifth load case concentrate the highest intensity in the center of the shell (indicate by B in the Figure 11.53).

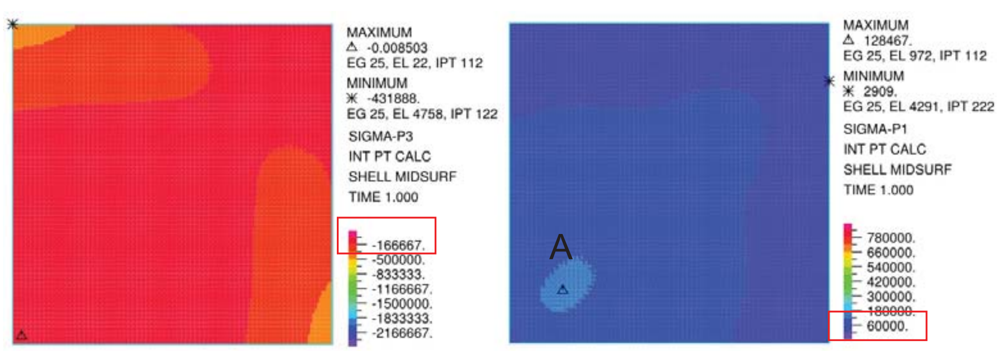


Figure 11.52 – LC4 (P3 left, P1 right) Midsurface [Pa]

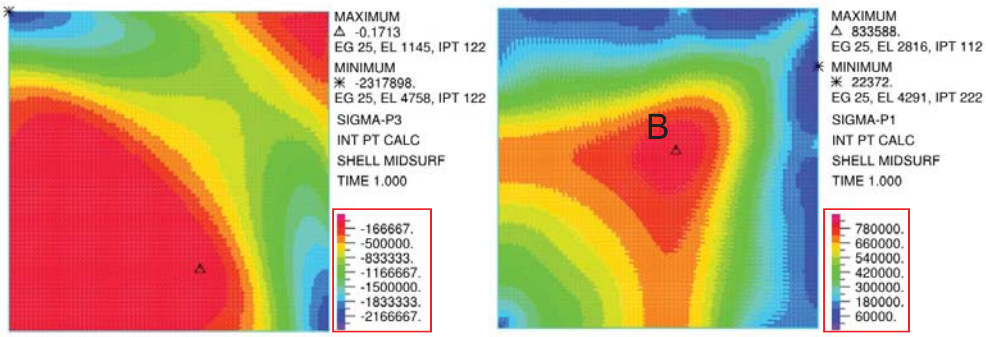


Figure 11.53 – LC5 (P3 left, P1 right) Midsurface [Pa]

The distribution of principal stresses is studied also through the thickness, on top and bottom surface (Figure 11.54 and Figure 11.55). The introduction of posts is changing the behavior of the structure in both compression and tension behavior.

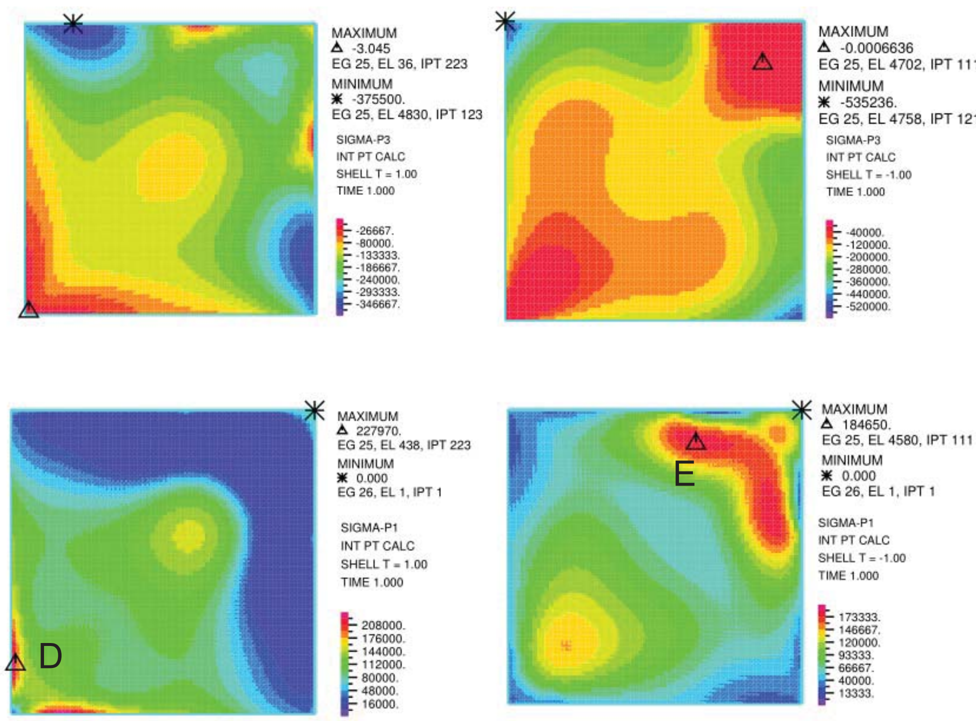


Figure 11.54 – LC4: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

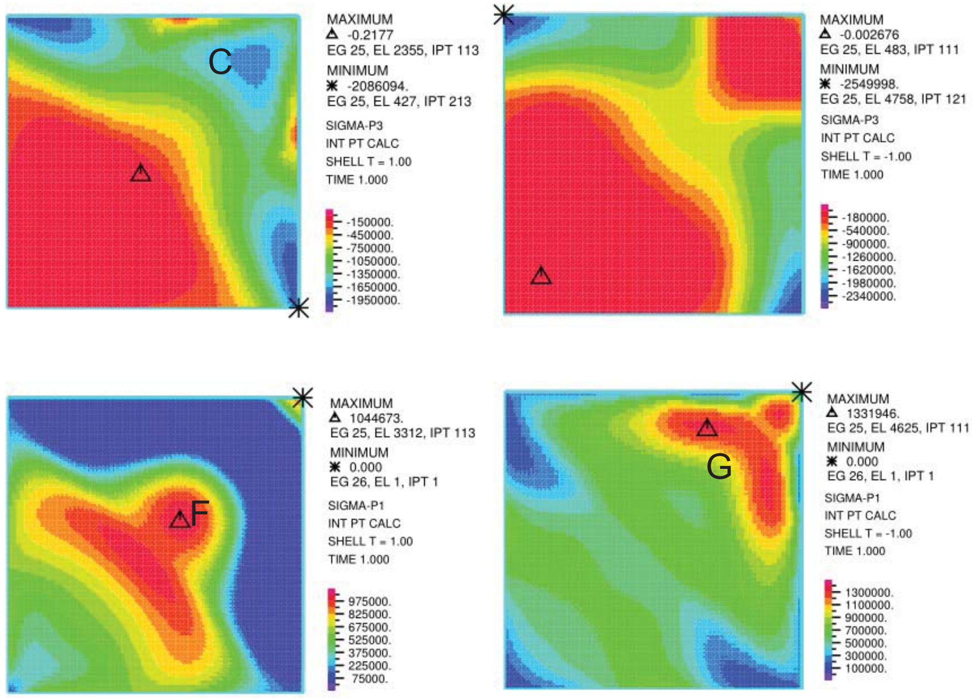


Figure 11.55 – LC5: Principal stresses (P3 above, P1 below) top and bottom surface (left, right)

Regarding the compression, the main difference, respect the previous cases, is that is not concentrated only in the supports but also in the corner between the tilted edges. This concentration is particularly relevant, due to the high intensity, in the fifth load case (indicated with C in Figure 11.55), since in this area the principal direction is at 45° and this means that the allowable stress needs to be divided by three in according to the APA (The Engineered Wood Association, 1997) recommendations. As already did in the previous cases the compression in these areas is called “Max 45P3” and they are compared with the related strength in the quantitative analysis.

In tension, the fourth load case induces to high principal stresses in two opposite areas: the first is on top surface in the horizontal edges, close to their shared corner (indicated with D in the Figure 11.54); the second is on the bottom surface close to the corner between the tilted edges (indicated by E in Figure 11.54). Due to the low intensity of stresses induced by this load case, only the maximum principal stress is considered in the quantitative comparison concerning the LC4.

Also the fifth load case induces to high tension in two different areas: on the top surface the tension is highly concentrated in the central area of the shell (F in the Figure 11.55), while on the bottom surface is more concentrated in the corner between the tilted edges (G in the Figure 11.55) as in the LC4. In LC5 the highest tension value is on the bottom surface but on the quantitative comparison is considered also the highest value in the top surface (F in Figure 11.55) as it has a high intensity.

Taking into account the qualitative considerations, Table 11.24 and Table 11.25 summarize the comparison between stresses and strength in according to the principal direction along which the stress is acting. The Figure 11.56 and Figure 11.57 show the location of the principal stresses compared with the strengths and the scheme of the principal directions of the shell.

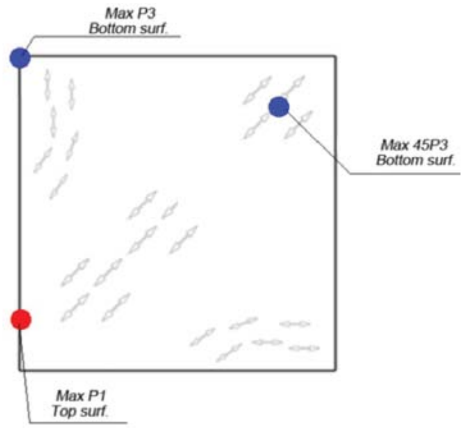


Figure 11.56 - Principal directions and location of maximum stresses LC4

Table 11.24 - Comparison stresses/strength LC4

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-0,54	-6,83	**0,08**
Max 45P3	**Fc/3**	**3P3/Fc**
-0,29	-2,28	**0,13**
Max P1	**Ft/6**	**6P1/Ft**
0,23	1,38	**0,16**

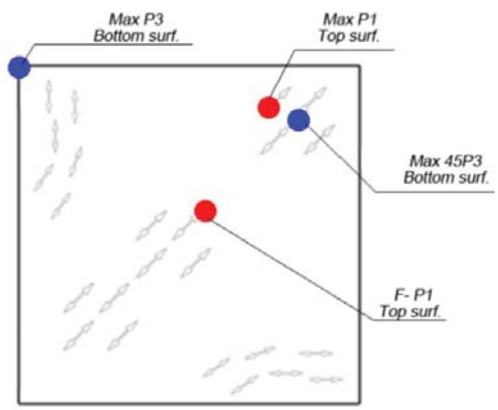


Figure 11.57 - Principal directions and location of maximum stresses LC5

Table 11.25 - Comparison stresses/strength LC5

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,26	-6,83	**0,37**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,80	-2,28	**0,79**
Max P1	**Ft/6**	**6P1/Ft**
1,33	1,38	**0,97**
F-P1	**Ft/6**	**6D/Ft**
1,05	1,38	**0,76**

From the quantitative comparison is possible to conclude that stresses that were considered as critical, due to their location and intensities, are lower than the strengths (compressive and tensile). The only case where the situation can be considered as critical is the maximum principal tension in the LC5, since the ratio stress/strength is 0,97.

The Figure 11.58 shows the vertical displacement of the diagonal that connects the corner between the horizontal edges with the opposite one. The graph confirms the high difference between the two load cases. The LC5 induces the highest displacement (approximately 1,9 [cm]) and is located at a distance of around 12 m from the corner.

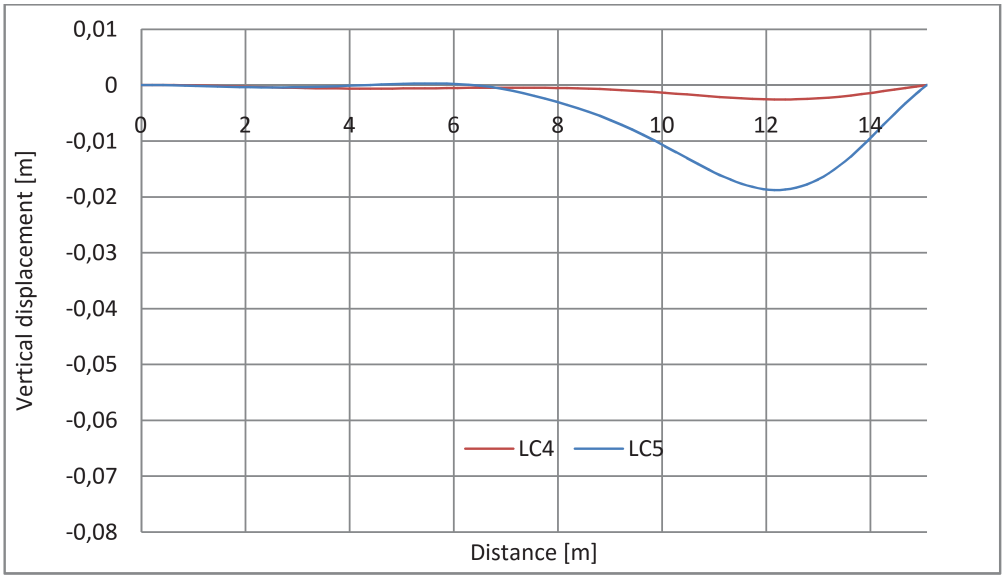


Figure 11.58 – Vertical displacement of the diagonal

11.3.4 Fourth Configuration – 4th

LC1-LC2-LC3

The Table 11.26 summarizes the maximum values of the principal stresses in the mid surface for the all the three load cases. It confirms what already noticed in all the previous cases analyzed. The maximum compression in the mid surface is reducing, about 50%, moving from LC1 to LC3. The tension is reducing from LC1 to LC2 but in the third load case is increasing of about 10% respect the LC1.

Table 11.26 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% difference between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC1	Max	-2,54	0,78	69	0	0
	Min	0	0			
LC2	Max	-1,21	0,57	53	-52	-26
	Min	0	0			
LC3	Max	-1,35	0,90	34	-47	15
	Min	0	0			

Comparing the results (maximum stresses in the mid surface) obtained in this case with the situation where the edges are clamped, the changes are not significant since the ratios between the stresses in the two cases are around the value 1 (Table 11.27).

Table 11.27 - Comparison of maximum stresses on mid surface between 3rd and 4th configurations

		3rd Configuration		4th Configuration			
		P3C [MPa]	P1C [MPa]	P3H [MPa]	P1H [MPa]	P3C/P3H	P1C/P1H
LC1	Max	-2,41	0,82	-2,54	0,78	**0,95**	**1,05**
	Min	0	0	0	0		
LC2	Max	-1,13	0,57	-1,21	0,57	**0,93**	**0,99**
	Min	0	0	0	0		
LC3	Max	-1,27	0,90	-1,35	0,90	**0,94**	**1,00**
	Min	0	0	0	0		

The maximum intensity of the compressive stresses is localized in the support between tilted and horizontal edges for the all three load cases. However, as it was happening in the third configuration, high values of compressive stresses can be found also in the central area of the shell (specially in LC3 – A in Figure 11.61) .

Concerning the stress P1, in the load cases two and three is localized in the corner between the horizontal edges, while in the first load case is localized in the center area of the shell. The band plots (Figure 11.59, Figure 11.60 and Figure 11.61) show the distribution of stresses in the mid surface.

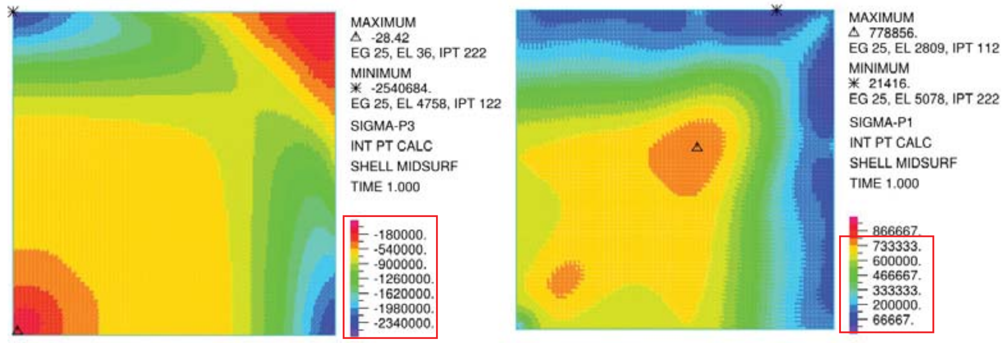


Figure 11.59 - LC1 (P3 left, P1 right) Midsurface [Pa]

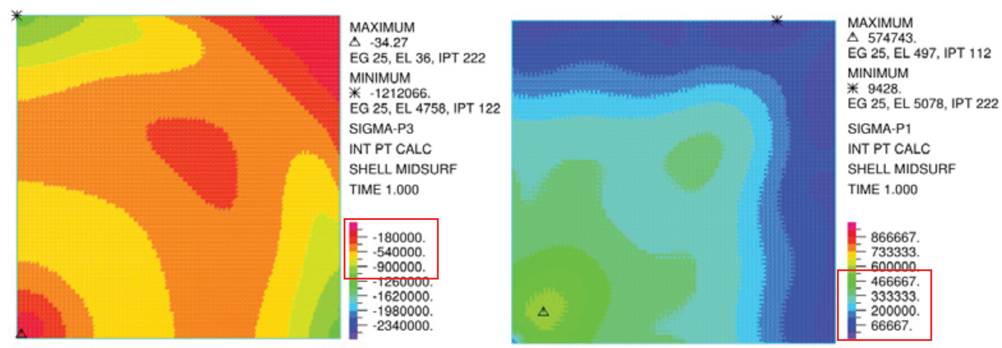


Figure 11.60 – LC2 (P3 left, P1 right) Midsurface [Pa]

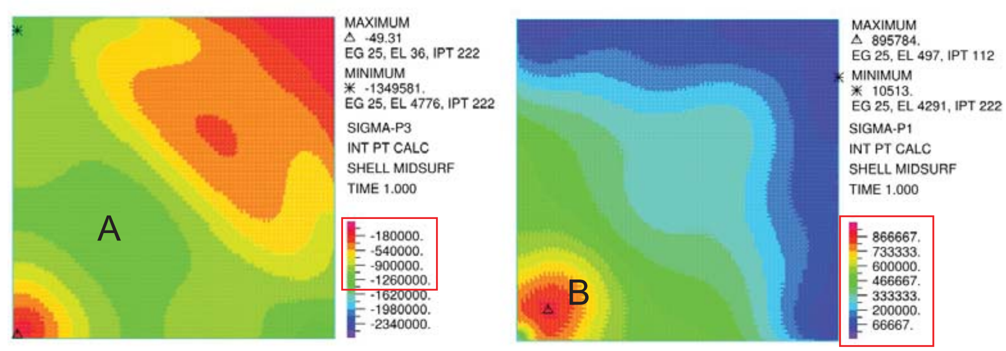


Figure 11.61 – LC3 (P3 left, P1 right) Midsurface [Pa]

The band plots show also that in the first load case the principal tensile stress is distributed along the central area, but shifting in the third load case it becomes much more concentrated in the corner of the shell (B in Figure 11.61). The compression, as in the previous case, is moving from the area between the tilted edges to the area between the horizontal ones.

The qualitative considerations done only in the mid surface are not enough for a deeply understanding of the structural behavior of the shell. The band plots of the principal stresses distribution are plotted also at the top and bottom surface (Figure 11.62, Figure 11.63 and Figure 11.64).

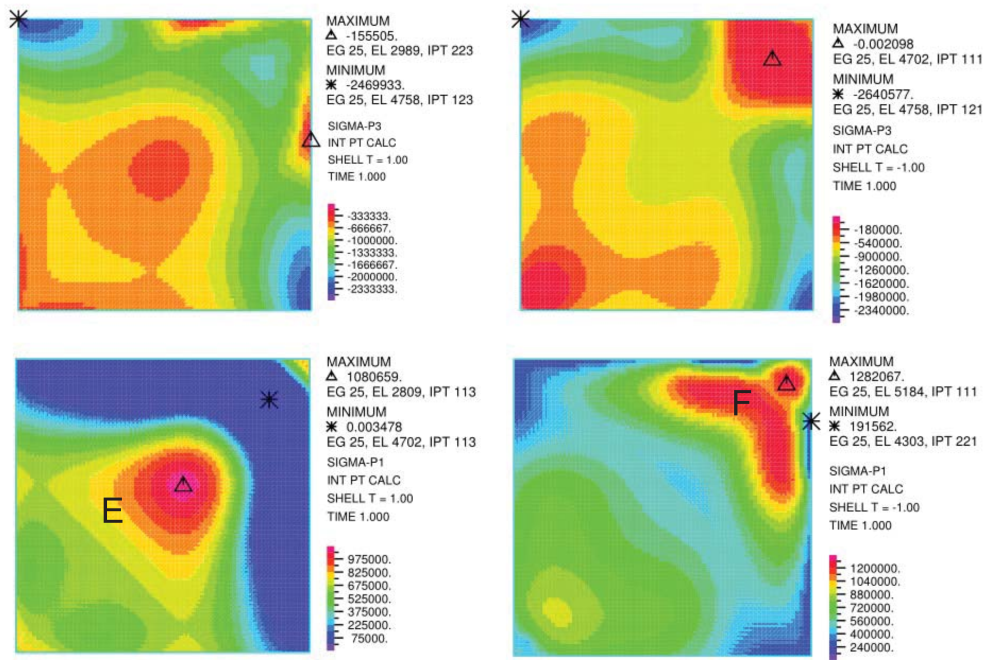


Figure 11.62 – LC1: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

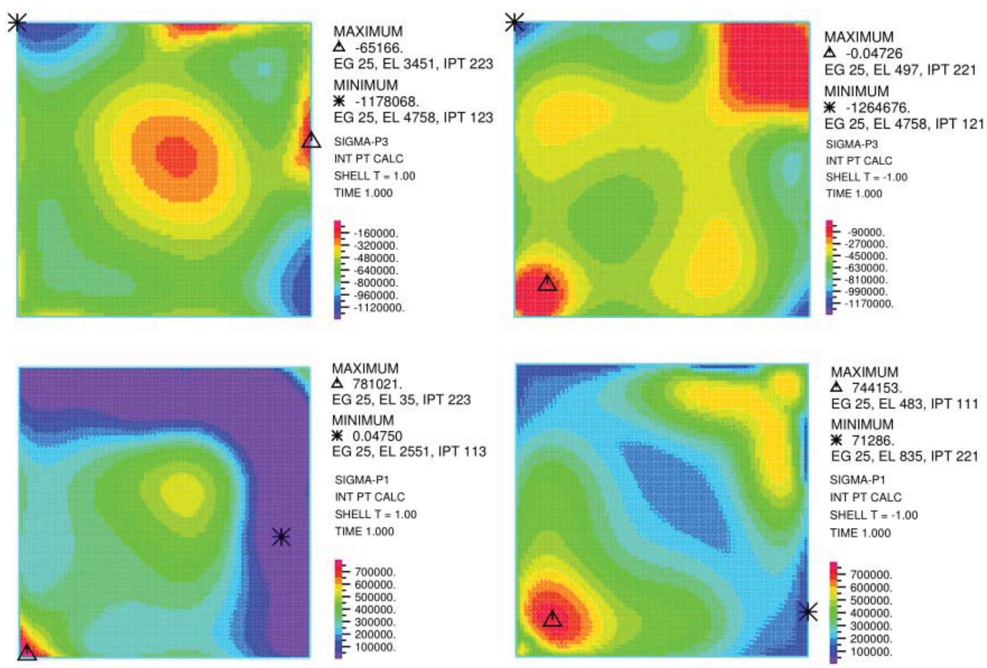


Figure 11.63 – LC2: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

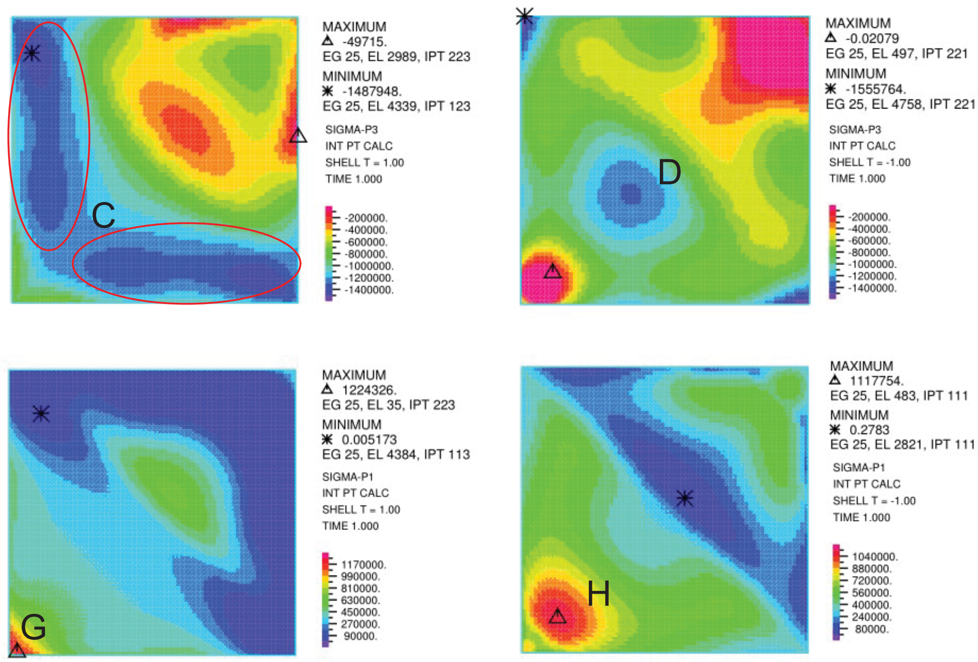


Figure 11.64 – LC3: Principal stresses (P3 above, P1 below) top and bottom surface (left, right) [Pa]

The plotting of the principal stresses through the thickness (top and bottom) shows that, regarding the maximum compression, in the first two load cases is concentrated in the supports between tilted and horizontal edges. In the third load case its maximum intensity on the top surface is more distributed in the areas parallel to the horizontal edges (C in Figure 11.64), while in the bottom surface is always localized in the supports. Moreover it is found a concentration also in the central area of the shell (D in Figure 11.64).

Concerning the tension, what already mention in the qualitative considerations of the results in the mid surface is also confirmed in the plotting through the thickness. The first load case has two areas of high concentration of stresses.

These two areas are the central part of the shell, in the top surface (E in Figure 11.62), and the corner between tilted edges, in the bottom surface (F in Figure 11.62). By increasing the load of the snow in the area between the horizontal edges, the tensile stresses increase, in a special way in the corner (G in Figure 11.64). The highest values is found in the top surface and concern the support between the horizontal edges.

In Figure 11.65, Figure 11.66 and Figure 11.67 are shown the values used in the quantitative comparison (Table 11.28, Table 11.29 and Table 11.30).

The quantitative comparison highlights that in the case where the posts are considered as structural elements and the horizontal edges as hinged, no load case represent a dangerous situation as all the maximum principal stresses induced are lower than the strengths. The only configuration that can be considered as critic is the maximum principal tensile stress induced in the first load case, since the ratio stress/strength is 0,93.

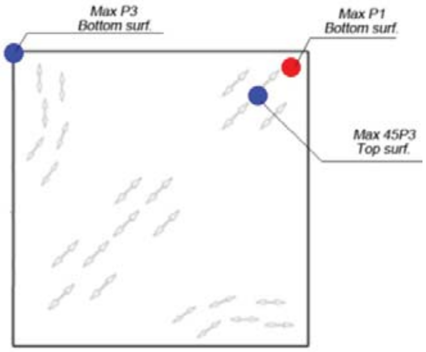


Figure 11.65 - Principal directions and location of maximum stresses LC1

Table 11.28 – Comparison stresses and strengths LC1

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,64	-6,83	**0,39**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,83	-2,28	**0,80**
Max P1	**Ft/6**	**6P1/Ft**
1,28	1,38	**0,93**

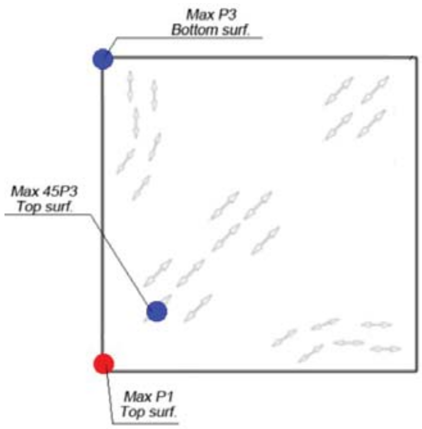


Figure 11.66 - Principal directions and location of maximum stresses LC2

Table 11.29 – Comparison stresses and strengths LC2

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-1,26	-6,83	**0,19**
Max 45P3	**Fc/3**	**3P3/Fc**
-0,88	-2,28	**0,39**
Max P1	**Ft/6**	**6P1/Ft**
0,78	1,38	**0,57**

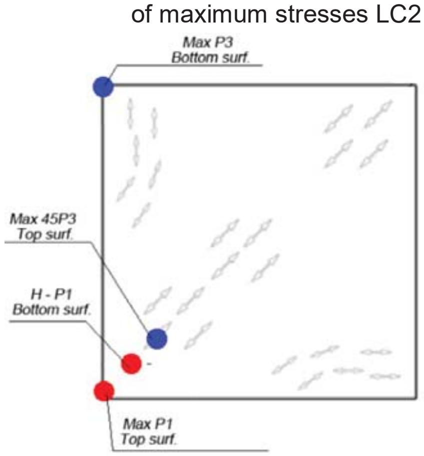


Figure 11.67 - Principal directions and location of maximum stresses LC3

Table 11.30 – Comparison stresses and strengths LC3

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-1,56	-6,83	**0,23**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,27	-2,28	**0,56**
Max P1	**Ft/6**	**6P1/Ft**
1,22	1,38	**0,89**
H-P1	**Ft/6**	**6D/Ft**
1,11	1,38	**0,81**

The vertical displacement of the diagonal (from the corner of the horizontal edges to the opposite), Figure 11.68, highlights that the change from clamped to hinged edges is not affecting significantly the deformed shape in terms of maximum displacements.

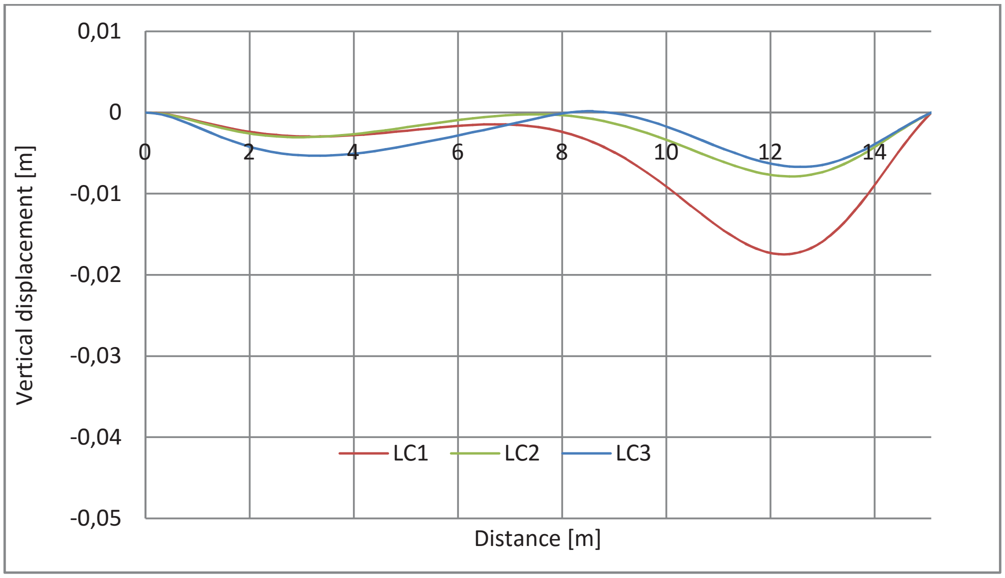


Figure 11.68 – Vertical displacement of the diagonal

LC4-LC5

The changing of the boundary conditions in the horizontal edges, from clamped to hinged, cause an increasing of the maximum principal compression stresses in the mid surface for both load cases. In tension, the stresses are getting higher but not in a significant way (Table 11.32). The Table 11.31 shows the maximum principal stresses in the mid surface for both cases, and it confirms that also in this configuration the intensity of the stresses induced by the fourth load case are relatively small compared to the fifth load case.

Table 11.31 - Maximum principal stresses on mid surface

				Difference Inside the Load case	Difference between Load cases	
		P3 [MPa]	P1 [MPa]	% difference between P1-P3 (in magnitude)	% difference P3 (in magnitude)	% differentce P1 (in magnitude)
LC4	Max	-0,50	0,12	76	0	0
	Min	0	0			
LC5	Max	-2,47	0,82	67	392	594
	Min	0	0			

Table 11.32 - Comparison of maximum stresses on mid surface between 3rd and 4th configurations

		3rd Configuration		4th Configuration			
		P3C [Pa]	**P1C [Pa]**	**P3H [Pa]**	**P1H [Pa]**	**P3C/P3H**	**P1C/P1H**
LC4	**Max**	-0,43	0,13	-0,50	0,12	**0,86**	**1,08**
	Min	0	0	0	0		
LC5	**Max**	-2,32	0,83	-2,47	0,82	**0,94**	**1,01**
	Min	0	0	0	0		

Observing the band plots of the principal stresses in the mid surface, and comparing them with the case with clamped edges, is possible to notice that there are not significant differences in terms of compression, while more differences can be found in tension. In the fourth load case the tension is not concentrated in the corner between the horizontal edges, as in the case of clamped boundaries, but is more uniformly distributed. In the LC5, the hinged boundaries concentrates more the mid surface stresses in the central area of the shell (indicated with A in Figure 11.70).

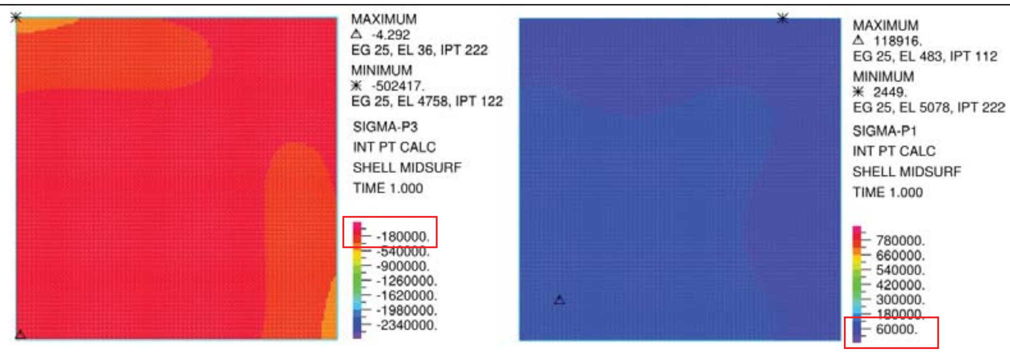


Figure 11.69 – LC4 (P3 left, P1 right) Midsurface [Pa]

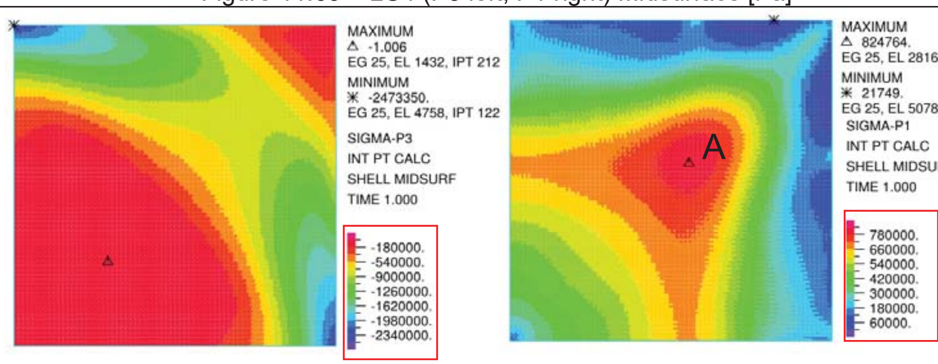


Figure 11.70 – LC5 (P3 left, P1 right) Midsurface [Pa]

The results obtained through the linear elastic analysis are evaluated also through the thickness (Figure 11.71 and Figure 11.72), as done in the previous cases. From the discussion of these last results is carried out that the behavior of the structure is more sensitive to the boundary conditions when the load is acting close to them. Indeed, in the fourth load case the main difference respect the case with clamped edges is in tension, since in this case it is more concentrated in the center of shell

(B in Figure 11.71) and in the support between the horizontal edges (indicated by C in Figure 11.71), while in the previous case was more concentrated in the in the connection with the edges.

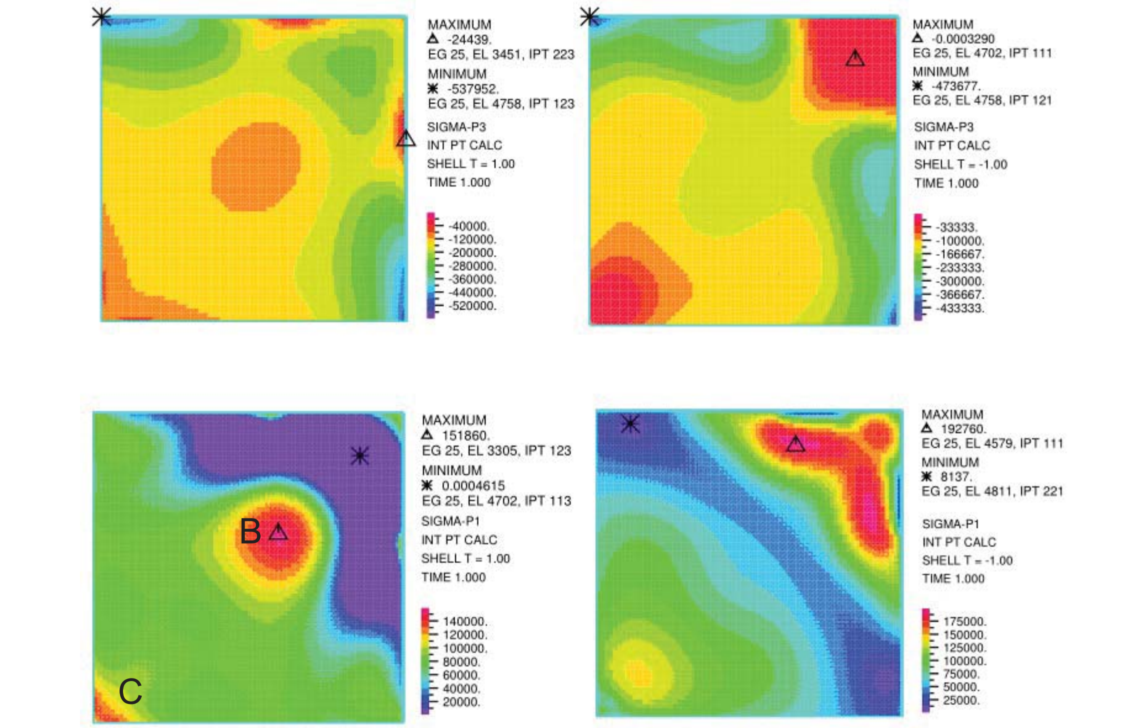


Figure 11.71 – LC4: Principal stresses (P3 above, P1 below) top and bottom surface (left, right)

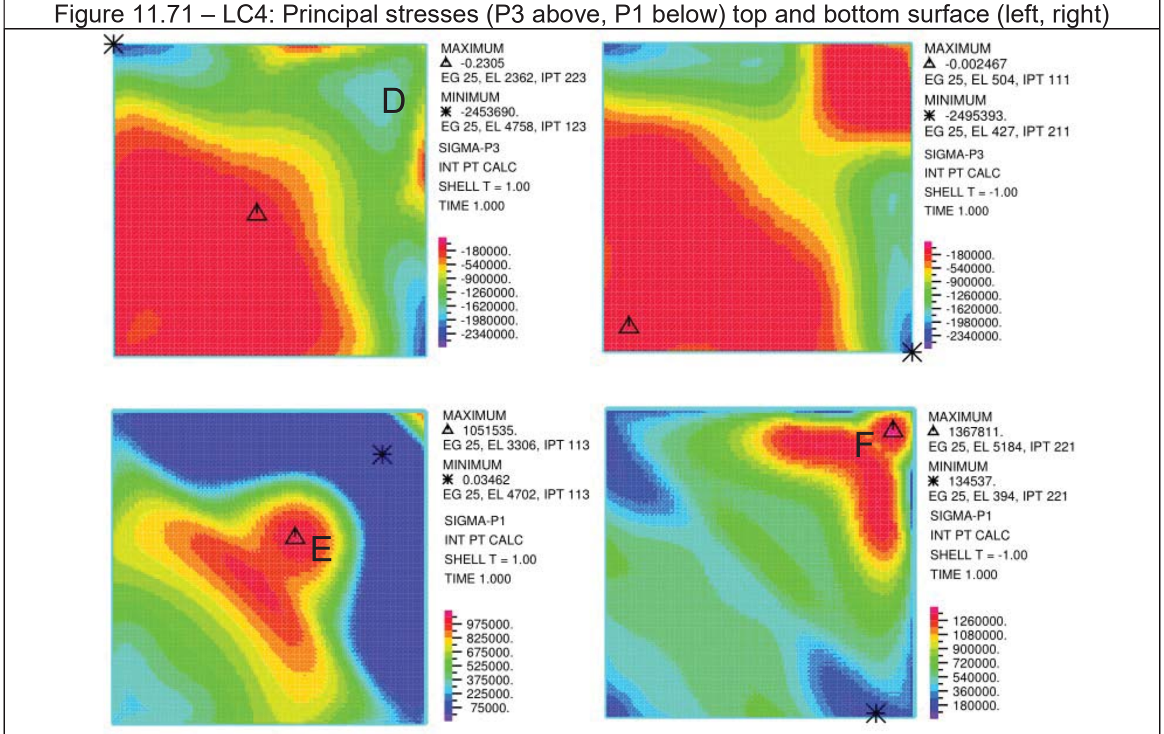


Figure 11.72 – LC5: Principal stresses (P3 above, P1 below) top and bottom surface (left, right)

In the quantitative comparison of the LC4 are taken only the maximum values, since this load case does not induce to high values of stresses. Concerning the fifth load case, the behavior of the structure is not deeply changing (in terms of intensity as already mentioned in Table 11.32 and in terms of distribution) from the clamped edges to the hinged edges.

The Figure 11.73 and Figure 11.74 show the stresses taken into account in the quantitative comparison and the directions of the principal stresses.

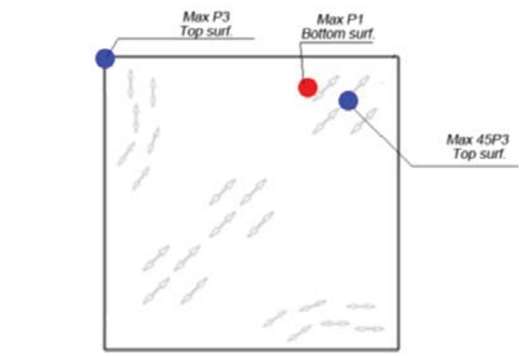


Figure 11.73 - Principal directions and location of maximum stresses LC4

Table 11.33 – Comparison stresses and strengths LC4

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-0,54	-6,83	**0,08**
Max 45P3	**Fc/3**	**3P3/Fc**
-0,28	-2,28	**0,12**
Max P1	**Ft/6**	**6P1/Ft**
0,19	1,38	**0,14**

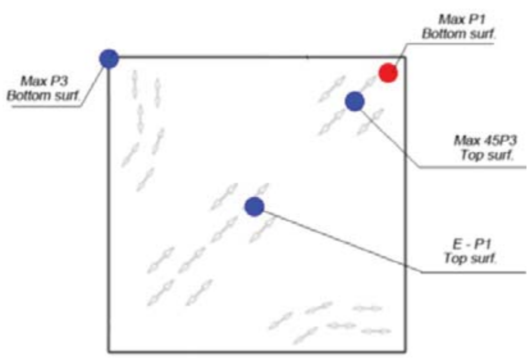


Figure 11.74 - Principal directions and location of maximum stresses LC5

Table 11.34 – Comparison stresses and strengths LC5

Point	Stress	P/S
[Mpa]	[Mpa]	[-]
Max P3	**Fc**	**P3/Fc**
-2,50	-6,83	**0,37**
Max 45P3	**Fc/3**	**3P3/Fc**
-1,80	-2,28	**0,79**
Max P1	**Ft/6**	**6P1/Ft**
1,37	1,38	**0,99**
E-P1	**Ft/6**	**6D/Ft**
1,05	1,38	**0,76**

From this comparison (Table 11.33 and Table 11.34) is carried out that the critic situation correspond to the fifth load case. The criticality is represented by a high tensile stress close to the support between the tilted edges (F in Figure 11.72). In these area the stress has almost the same value as the strength.

The vertical displacement of the diagonal is shown in Figure 11.75 and confirms the fact that the deformation is not significantly changing since the LC5 is acting far from the horizontal edges where the boundaries are changed.

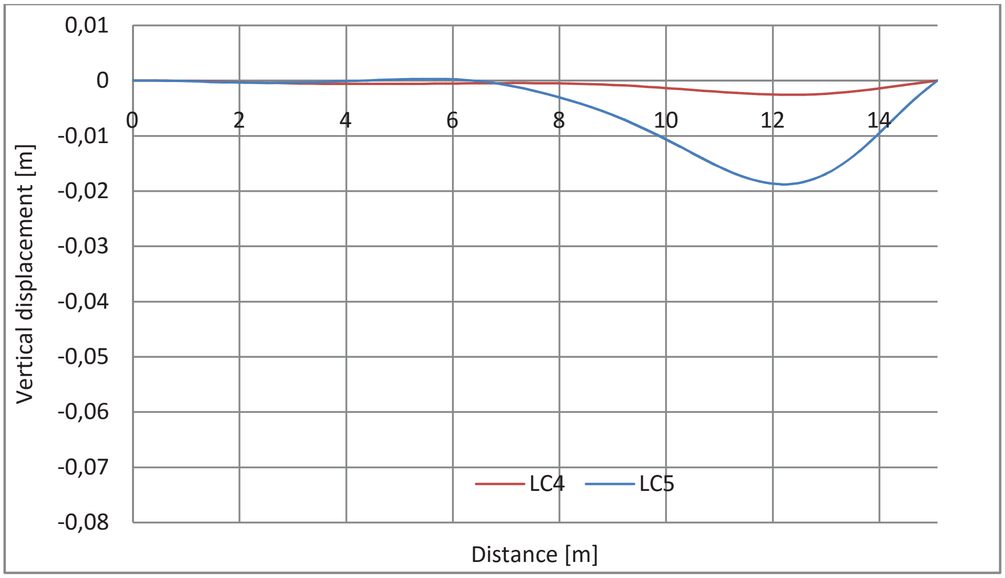


Figure 11.75 – Vertical displacement of the diagonal

11.3.5 Shear Through the Thickness

In according to the APA specifications (The Engineered Wood Association, 1997) for the grading and definition of the mechanical properties (Chapter 11) of the plywood, the shear resistance is 827 [kPa]. For all the load cases and configurations the shear through the thickness is computed and the band plots are shown in the Appendix3. The Table 11.35 summarizes illustrates the maximum values for every load case and configurations.

Table 11.35 - Maximum shear stresses

	LC (Load case)				
	1	2	3	4	5
	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]
1st Configuration	937	497	816	193,00	930,00
2nd Configuration	1035	545	872	256,00	1058,00
3rd Configuration	766	491	811	119,00	764,00
4th Configuration	764	540	867	119,00	766,00

The comparison of these maximum values with the shear resistance ($F_v = 827[kPa]$) is shown in the Figure 11.76, where the red line represent the limit value of the strength.

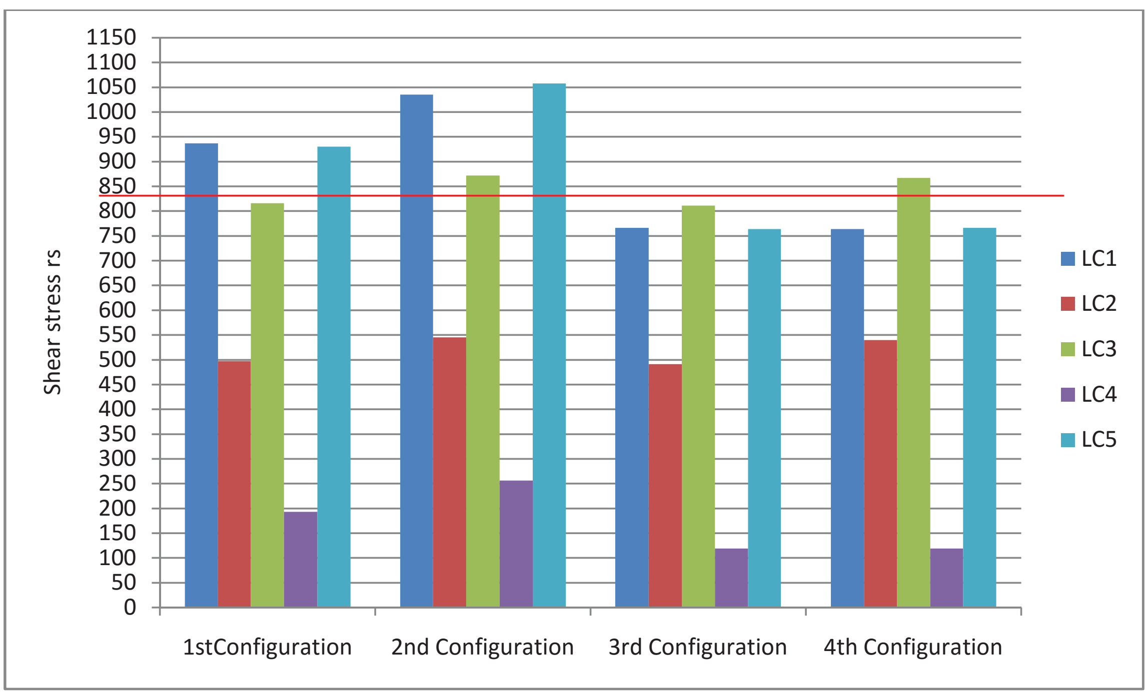


Figure 11.76 – Histogram: Max Shear Stress – Load Case - Configuration

Analyzing the Figure 11.76 it can be noticed that:

- The highest shear stresses occur in the first two configurations
- The shear strength of the plywood material is exceeded in first two configurations when LC1 and LC5 are applied
- LC3 shows small changes, in terms of maximum shear stress, between the all four configurations. The maximum shear stresses induced by this load case vary from 816 [kPa] to 872 [kPa]. In the second and fourth configurations the stresses induced are higher than the strength.
- The consideration of the horizontal edges as hinged lead to the increasing of the stresses, meanwhile with the addition of the posts the stresses decrease.

The band plots in the Appendix 3 highlight that the LC1 and LC5 present similar distribution of the shear stress. In the 1st Configuration their maximum is localized close to the corner between the tilted edges, while in the 2nd Configuration a concentration of stresses in this area still remains but the maximum value is located in the supports between horizontal and tilted edge.

The band plots of the LC3 present a similar distribution in all the configurations, confirming the small variation of the maximum shear stress between the different configurations, and the maximum value is close to the corner between the horizontal edge.

The Figure 11.36 summarize the situations considered as critical because the stresses are higher or close to the strength.

Table 11.36 - Critical (concerning shear through thickness) load cases

Configuration	Load Case	Stress/Strength	Localization	Surface	Reference
1st	LC1	1,13	Close to corner between tilted edges	Mid	Figure 16.1 – Appendix 3
	LC5	1,12	Close to corner between tilted edges	Mid	Figure 16.5 - Appendix 3
2nd	LC1	1,25	Support between tilted and horizontal edges	Mid	Figure 16.6 - Appendix 3
	LC3	1,05	Close to the corner between the horizontal edges	Mid	Figure 16.8 - Appendix 3
	LC5	1,28	Horizontal edges, close to their corner	Mid	Figure 16.10 - Appendix 3
4th	LC3	1,05	Close to corner between tilted edges	Mid	Figure 16.18 - Appendix 3

11.3.6 Axial Force in the Posts

The posts are considered only in the third and fourth configuration. Indeed for every load case and configuration the axial force in the posts is computed and shown in the Table 11.37. The post in the corner between the tilted edges is called "Corner" , meanwhile the other two "Lateral" (Figure 11.77).

The lateral posts are not differentiated because they are affected by the same stresses since the structure, loads and boundaries are symmetric. In the assessment of the posts two aspects are taken into account: the first is the material resistance and the second is the buckling. For this reason two critical axial forces are defined:

$$N_{cr\ material} = F_c A$$

$$N_{cr\ buckling} = \pi^2 \frac{EI_{min}}{{L_0}^2} \qquad (66)$$

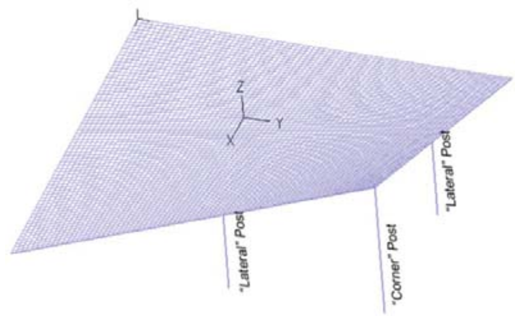


Figure 11.77 – "Corner" and "Lateral" Posts

where:

- Fc : is the compression strength
- A: area of the cross section
- I_{min}: minimum moment of inertia
- L_0: influence length of the post and since have been model as hinged L_0 is equal to L
- E: young modulus

The mechanical properties of the posts are defined in the Chapter 11 (Mechanical Characterization) in according with the grading provided by Professor David Biggs. Considering their geometry and their mechanical properties the two critical axial forces are computed for the lateral and corner posts and shown (Table 11.37). In the same table are shown also the maximum axial forces that every load case and configuration induce in the posts. Through this comparison is carried out that the posts do not represent an issue for any load case and configuration.

Table 11.37 - Comparison axial forces and axial resistance

		LC (load case)					Ncr	
		1	2	3	4	5	Material	Buckling
	Post	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
3rd Configuration	Lateral	10,43	5,57	5,134	2,76	10,91	**23,13**	**91,37**
	Corner	5,78	3,06	2,98	1,27	6,09	**34,70**	**44,75**
4th Configuration	Lateral	10,82	5,84	5,43	2,95	11,31	**23,13**	**91,37**
	Corner	5,83	3,10	3,07	1,27	6,10	**34,70**	**44,75**

11.4 Results Discussion

Maximum and Minimum Principal Stresses

The results in terms of principal stresses are discussed in the following firstly regarding the snow load and then wind load.

Snow load

The analysis of the results shown in the chapters above, pointed out that moving from clamped edges to hinged edges is reflected in an increasing of principal compressive stresses in the mid surface. However the compression in all configurations and load cases analyzed never showed a critic situation where the stresses are higher or close to the strengths. In tension, the maximum values on mid surface are similar between clamped and hinged edges, but the main difference is in the distribution of them, in particular in LC2 and LC3. Indeed, in these two load cases when the edges are clamped the tensile stresses are extremely localized and present high values in the connection between edges and shell layers. Moving to hinged edges the concentration of tensile stresses is directly in the support between the horizontal edges but is characterized by lower intensity than the clamped configurations. This behavior was found in all the four configurations analyzed. As an example is reported (Figure 11.78 and Figure 11.79) the comparison, in terms of principal tensile stresses P1 on top surface of the LC3, between 1st Configuration and 2nd Configuration.

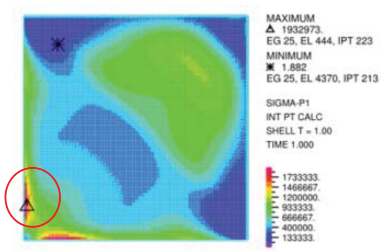


Figure 11.78 – 1st Configuration LC3- P1 Top

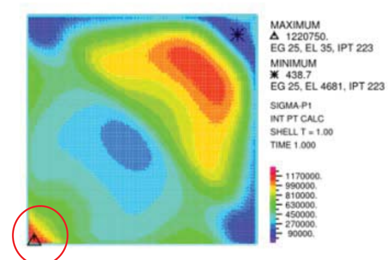


Figure 11.79 – 2nd Configuration LC3- P1 Top

The introduction of the posts as structural elements leads to a significant reduction of the compressive stresses but their distribution is changing. Without the post the stresses were more localized in the supports, while in configurations three and four, high compressive stresses are found also in the central area of the shell where the principal directions are at 45°. This has been analyzed, since in these areas the compressive strength need to be divided by three in according to the APA (The Engineered Wood Association, 1997) recommendations. The Figure 11.80 and Figure 11.81 show the distribution of P3 stresses on mid surface for LC1 in 1st and 3rd configuration.

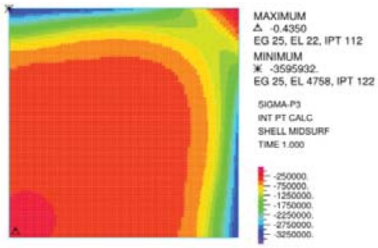


Figure 11.80 - 1st Configuration LC1- P3 Mid

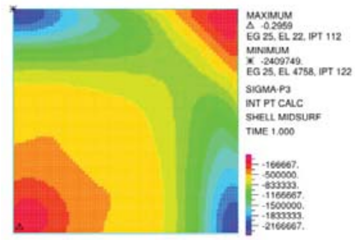


Figure 11.81 – 3rd Configuration LC3- P3 Mid

The considerations made about the tension behavior in the 1st and 2nd configurations are found also in the 3rd and 4th configurations.

The Table 11.38 presents for every configuration all the load cases considered as critical or dangerous since the ratio stress/strength is close to 1 or higher.

Analyzing the table is possible to say that the first configuration leads to critic situations for LC1 and LC3. Considering edges as hinged (2nd configuration) the LC3 does not induce anymore to any critic situation but the issue of LC1 still remains. Summarizing the dangerousness of the LC1 in the first configuration is reduced by introducing the posts as structural elements (3rd and 4th configurations). Regarding the LC3, the high stresses induced in the first configuration disappear when the horizontal edges are considered as hinged (2nd and 4th configurations).

Table 11.38 – Critical (in terms of principal stresses) snow load cases for every configuration

Configuration	Load Case	Stress/Strength	Localization	Surface	Reference
1st	LC1 - Max P1	**1,4**	Close to corner between tilted edges	Top	Figure 11.9
	LC3 - Max P1	**1,4**	Horizontal edges, close to their corner	Top	Figure 11.11
2nd	LC1 - Max P1	**1,5**	Close to corner between tilted edges	Top	Figure 11.28
3rd	LC1 - Max P1	**0,98**	Horizontal edges, close to their corner	Top	Figure 11.45
	LC3 - Max P1	**1,4**	Horizontal edges, close to their corner	Top	Figure 11.47
4th	LC1 - Max P1	**0,93**	Close to corner between tilted edges	Bottom	Figure 11.62

Wind load

The fourth load case that considers a negative pressure of the wind load is not enough to have an uplifting of the roof, since the dead load has a higher intensity. As already mentioned, this load case was studied because wind and dead load have different direction so the final pressure will act in the surface differently in any point (Figure 11.82). However, the intensity of this load case is small compared with the fifth load case and it never leads to critic situation in all the configurations.

Critic situations are shown only in regarding to the fifth load case and mainly in the two first configurations, where the posts are not considered. This is mainly due to the fact that LC5 is acting in the area of the tilted edges, where (in 1st and 2nd configurations) there are no vertical supports.

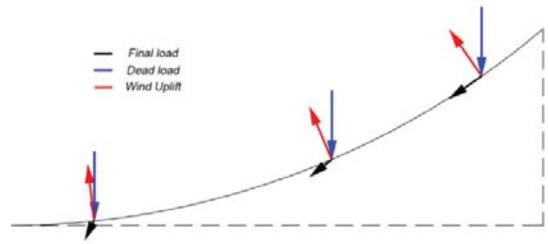


Figure 11.82 - Scheme of the wind uplift LC4

The boundaries conditions at the horizontal edges do not affect significantly the behavior of the structure under this load case. Only in the first configuration a critic situation with high tensile concentration of stresses in the horizontal edges is found (stress/strength = 0.94). In Table 11.39 are shown the critical load case for every configuration.

In the first two configurations the structure shows almost the same critical issues, highlighting that the boundaries at the horizontal edge do not affect the global behavior under the LC5, since the load is acting far from those boundaries. The addition of the posts as structural elements improves significantly the behavior of the structure. Indeed in the LC5 of the third configuration the maximum stress is close to the strength but not higher. Moreover in the 4th Configuration the structure does not show any critic situation for both load LC4 and LC5.

Table 11.39 – Critical (in terms of principal stresses) snow load cases for every configuration

Configuration	Load Case	Stress/Strength	Localization	Surface	Reference
1st	LC5 - Max P1	1,4	Close to corner between tilted edges	Top	Figure 11.19
	LC5 - P1 - E	0,94	Horizontal edges	Bottom	Figure 11.19
2nd	LC5 - Max P1	1,48	Close to corner between tilted edges	Top	Figure 11.38
3rd	LC5 - Max P1	0,97	Close to corner between tilted edges	Top	Figure 11.55

Displacements of the Diagonal

The vertical displacement of the diagonal that connect the corner between the horizontal edges with the opposite corner showed that is more affected by the presence of the posts than the boundaries at the horizontal edges. The influence of the post in the vertical displacement is clearly shown in the Figure 11.83 that present the displacement of the diagonal under the dead load in all four configurations.

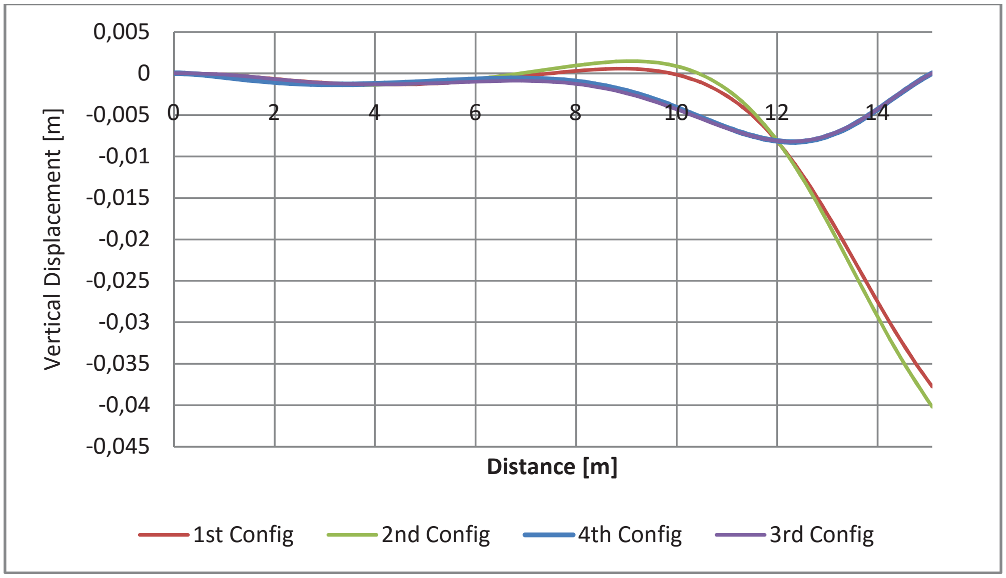


Figure 11.83 - Vertical displacement of the diagonal under dead load - 4 configuration

Shear Through the Thickness τ_{st}

The results obtained in terms of shear through the thickness showed that the most critical situations are found in the 1st and 2nd configurations. The vulnerabilities are due to the LC1 and LC5. The introduction of the posts improves the structural behavior of the shell in terms of stresses, since in the 3rd and 4th configurations the LC1 and LC5 do not induce to any critical situations. The only load case that is not influenced by the changing of the boundary conditions at the horizontal edges or the introduction of the posts is the LC3, since its maximum values are in all the configurations close to the limit value of the stress.

Axial Forces in the Posts

The linear elastic analysis performed for the different configurations and load cases have shown that, in terms of axial forces on the posts, there are no limit situations where the strength is reached or exceeded.

12. CONCLUSIONS

The numerical analysis carried out in this work has as a background an important process of knowledge of hyperbolic shallow shells' theory. The first step consisted of comparison between the simplified design rules (West Coast Lumbermen's Association, 1964) and the FE model; this comparison showed a 2% difference between the results (in terms of reactions, shear stress and compression along the edges) and therefore confirms the accuracy of the simplified design rules. However, the limits of those design rules are represented by the geometry conditions of the structure. Indeed they are developed for leveled hyppar structures. When a structure is tilted, as in the case of Nakashima Arts Buildings, the normal stresses increase significantly therefore making the assumptions of the simplified rules no longer valid. The second step was related with the verification of the FE model; the numeric model was verified since the analytical solution, developed through the theory of shallow shells (Blaauwendraad and Hoefakker, 2014), and the numerical solution differ in terms of shear stresses by a maximum of 15%. Furthermore in bending behavior, both solutions presented similar distribution of moments and influence lengths.

Based on the numerical analyses carried out for different boundary conditions and load cases, the posts of the Nakashima Arts Building do not suffer buckling instability. The main issues of the structure concern the shear through the thickness and the tensile behavior, since in mostly all configurations a critic situation has been found.

Through the results obtained it was found that the most vulnerable situation for the roof structure occurred in the configuration where the horizontal edges are considered as hinged and the contribution of the posts is neglected. In this configuration the vulnerabilities concern both, shear through the thickness and tensile stresses and are induced mainly by the LC1, LC3 and LC5.

In terms of shear stresses through the thickness, considering the structure as clamped or hinged does not influence significantly the structural behavior. The situation improves only when the posts are introduced as structural elements in the 3rd and 4th configurations. However, this improvement does not affect the LC3 which remains a critical load case in all the four configurations.

Regarding the principal tensile stresses, considering the edges as clamped or hinged produces a larger effect on the behavior of the structure under the LC3. This is mainly due to the fact that LC3 is acting in the area close to the boundary conditions. The addition of the posts improves the shell's structural behavior for LC1 and LC5.

In reference to the snow load, its uniform distribution all over the shell induces the highest values of principal tensile stresses. The most vulnerable region of this load case is the area close to the corner between the tilted edges, with exception of the 3rd configuration where the vulnerability is located along the horizontal edges close to the corner. Moreover, LC3 (half of the snow load swept onto half area of the shell) also represents a critical situation for the structure since in the 1st and 2nd configurations the tensile stresses exceed the strength. The vulnerability shown in this load case is located along the horizontal edges close to their shared corner. This is considered to be particularly dangerous because it is highly concentrated and concern the connection with the edges.

The wind load represents a critical load case for the roof structure only when it is acting downward in half of the area of the shell (LC5). In the 1st configuration, LC5 is inducing vulnerabilities in two areas: close to the corner between the tilted edges and in the horizontal edges. Considering the horizontal edges as hinged, the vulnerability is reduced only to the corner between the tilted edges. Introducing the posts as structural elements the vulnerability is reduced and in the fourth configuration LC5 does not induce any critical situations. The uniform uplift (LC4) is not leading to vulnerabilities since is not intense enough to unbalance the dead load. The results obtained through the analyses of various boundaries and load cases are suitable to be used for three different purposes:

- Planning the ordinary maintenance: from the numerical analysis was observed that the uniform distribution of the snow induce vulnerabilities in all the configurations. It is therefore suggested to keep the structure free from the snow load. Moreover, if the real behavior of the structure is close to the 4th configuration, the snow distribution as LC3 does not induce vulnerabilities in terms of principal tensile stresses, while in terms of shear through the thickness the maximum stress is similar to the shear strength. This underlines that is necessary to investigate the real behavior of the structure. Through the results of this investigation it will be possible to define with more accuracy the weakness of the structure under a specific load distribution.

- Improving of the investigation plan: the vulnerabilities for every configuration and load case are localized mainly in two specific areas, in the corner between the tilted edges and along the horizontal edges. Is suggested to investigate these areas in order to check if there is any damage that could confirm the results of the numerical analysis. Moreover, an investigation on the connection between the posts and the tilted edges is needed, since the structural behavior is deeply changing when considering them as structural elements.

- Calibration of the model: Mr. Cesar Bargues Ballester has already performed a campaign of measurements on the underside of the roof structure subjected only to dead load and creep. In order to calibrate the model for further analysis, it is suggested to perform similar campaign during the wintertime. In this way it will be possible to have the deflections of the structure under the snow load. Through this “natural” load test it will be possible to check the real behavior of the structure. This process will also allow the calibration of the numerical model. Moreover, through the snow deflections it will be possible also to check the effectiveness of the posts.

The work carried out in this thesis could be a starting point for further numerical analysis where the plywood is modeled as an orthotropic material in order to better describe its real structural behavior. This analysis would allow for the safety assessment of the structure under the most critical load case and configuration. Through this consideration it will be then possible to evaluate if structural strengthening is needed.

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14. APPENDIX1: PLAN AND CROSS SECTION OF NAKASHIMA ARTS BUILDING

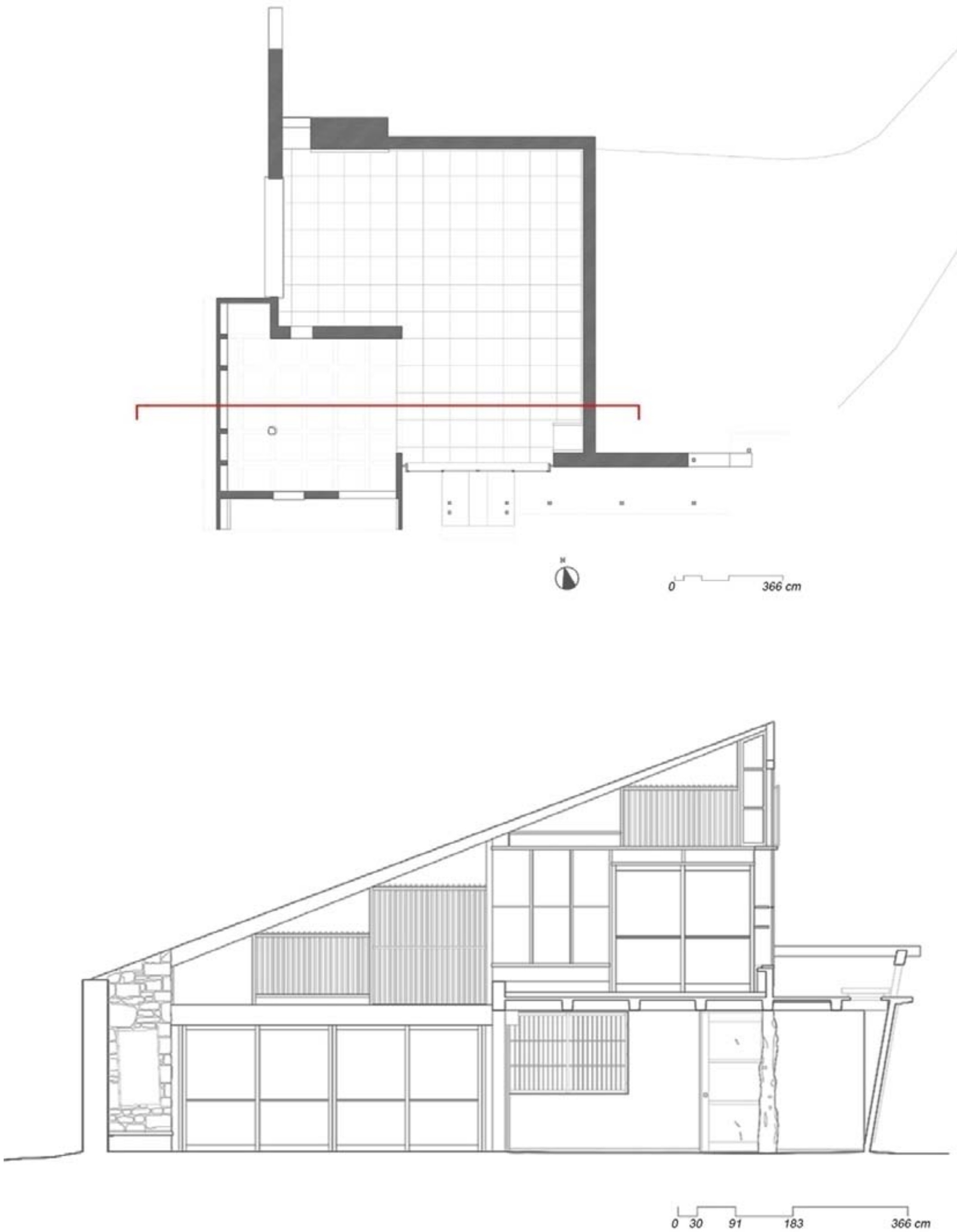

Figure 14.1 - Plan (above) and cross section (below) of Nakashima Arts Building

15. APPENDIX 2: DISCRETIZATION OF THE EDGE BEAMS AND CALCULATION OF THE MOMENTS OF INERTIA

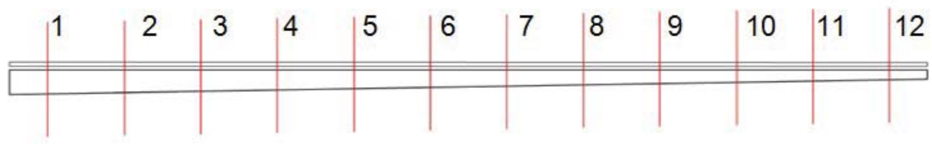

Figure 15.1 - Discretization of the Beam

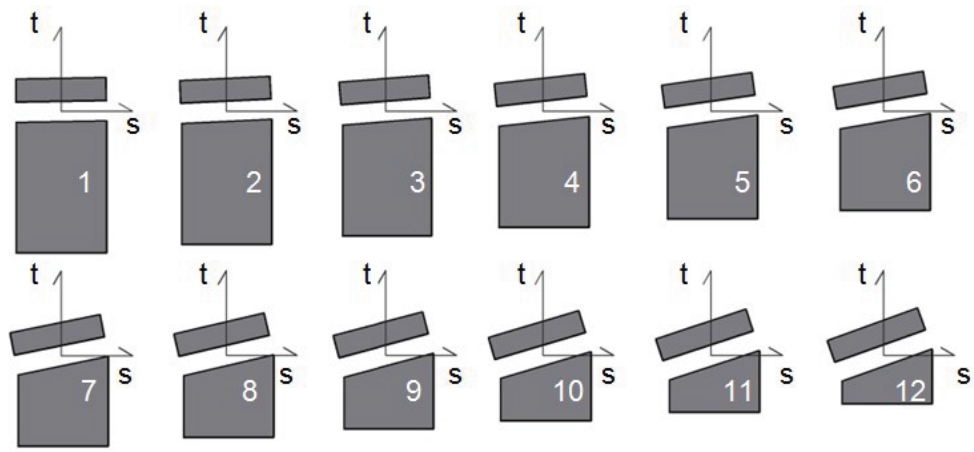

Figure 15.2 Cross Sections for the computation of the moments of inertia I_s, I_t, I_{ts}

Table 15.1 - Moments of inertia and product of inertia of the cross sections considered

	I_t	**I_s**	**I_{ts}**
Section	[cm^4]	[cm^4]	[cm^4]
1	222612	24208	456
2	185228	22920	1016
3	152312	21520	1424
4	123624	20192	1744
5	98896	18872	1936
6	77804	17760	2064
7	60024	16448	1936
8	45280	15328	1904
9	33388	14080	1728
10	23896	12912	1544
11	16664	11696	1240
12	11288	10576	984

16. APPENDIX 3: BAND PLOTS OF THE SHEAR THROUGH THE THICKNESS

The band plots shown in the following are computed at the mid-surface of the shell and the unit of the shear stress is [Pa].

1st Configuration

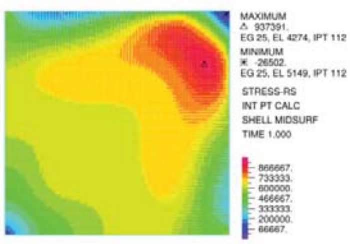

Figure 16.1 - LC1

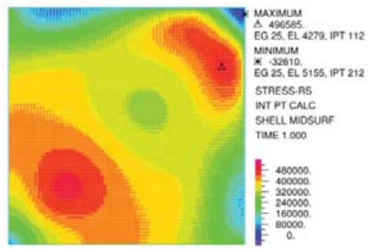

Figure 16.2 – LC2

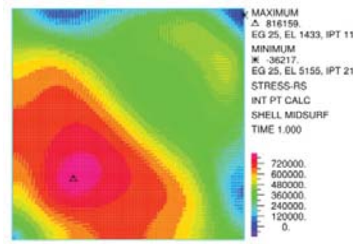

Figure 16.3 – LC3

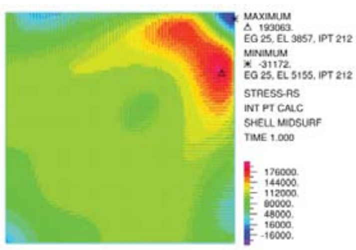

Figure 16.4 – LC4

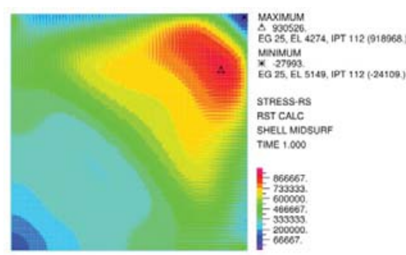

Figure 16.5 – LC5

2nd Configuration

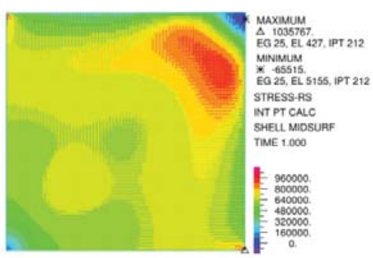

Figure 16.6 - LC1

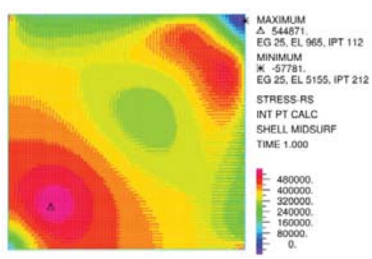

Figure 16.7 – LC2

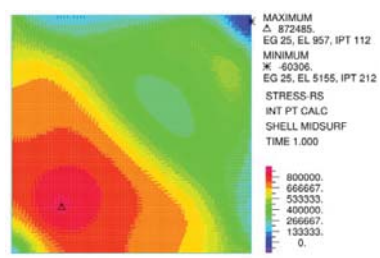

Figure 16.8 – LC3

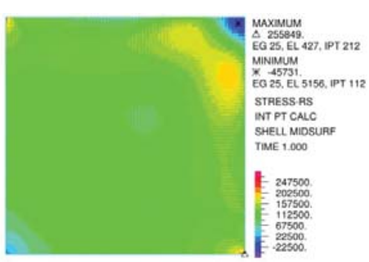

Figure 16.9 – LC4

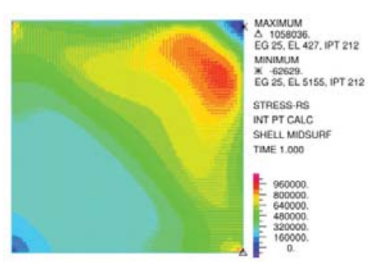

Figure 16.10 – LC5

3rd Configuration

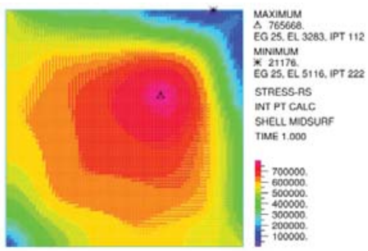

Figure 16.11 - LC1

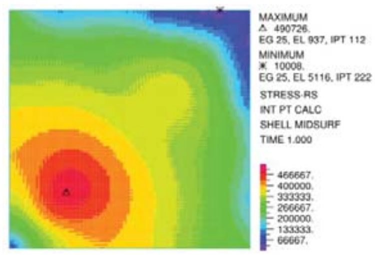

Figure 16.12 – LC2

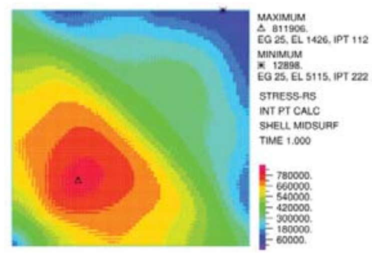

Figure 16.13 – LC3

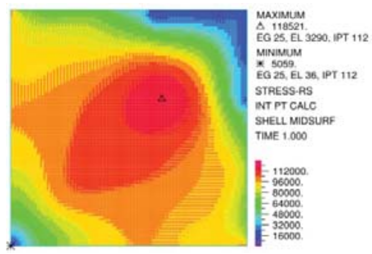

Figure 16.14 – LC4

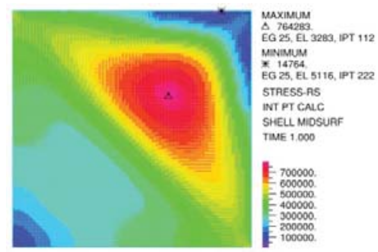

Figure 16.15 – LC5

4th Configuration

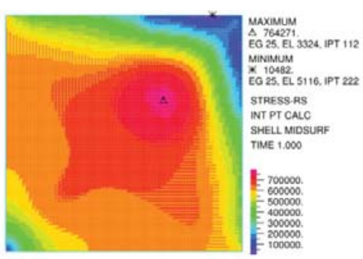

Figure 16.16 - LC1

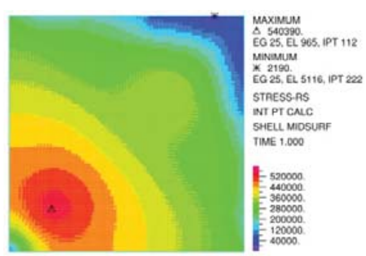

Figure 16.17 – LC2

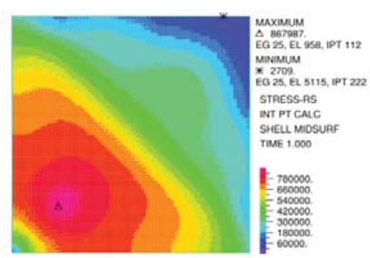

Figure 16.18 – LC3

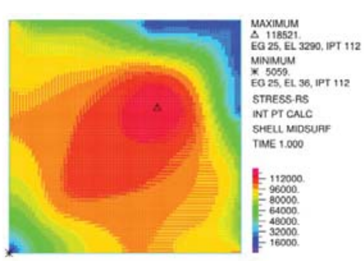

Figure 16.19 – LC4

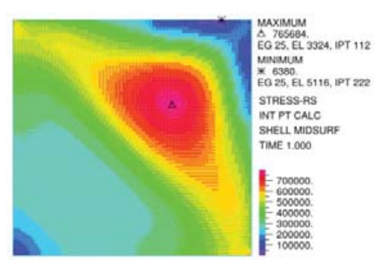

Figure 16.20 – LC5

Appendix B

Investigating the Preservation Needs of Objects within the
George Nakashima Arts Building.
Leah Bright,
Winterthur/University of Delaware Program in Art Conservation, 2016

Investigating the Preservation Needs of Objects within the George Nakashima Arts Building

A Research Project Carried Out to Fulfill the Preventive Minor
Winterthur, University of Delaware Program in Art Conservation

Leah A. Bright, WUDPAC Class 2017
May 13, 2016

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Investigating the Preservation Needs of Objects within the George Nakashima Arts Building

I. Project Background, Goals, & Process

George Nakashima (1905-1990) was an American woodworker and architect considered the father of the American craft movement and well known for his elegant conoid chairs and large slab tables that embrace the natural beauty of wood. Nakashima also founded the George Nakashima Institute for Peace to promote global peace through the crafting of peace altars for each continent. The nineteen buildings on Nakashima's estate near New Hope, Pennsylvania still function as home and workshop and the complex was listed as a National Historic Landmark in 2013.

One notable building on the estate is known as the Arts Building, which Nakashima designed in 1964-1967 to serve as a gallery for the artwork of his friend Ben Shahn (1898-1965), but sadly Shahn passed away in 1965 before construction was complete. The unique hyperbolic paraboloid roof of the building is of special interest to historic preservationists, and the building still holds many objects and works associated with Shahn, and a mosaic Shahn designed is installed on the exterior of the building. Today, the Arts Building serves as a museum and an example of Nakashima's skill as an architect and is the home of the Foundation for Peace. It is used for events and houses furniture, furniture prototypes, drawings, and archival materials in addition to the objects and works associated with Ben Shahn (Historic Structures Report, 2013).

In 2014 after the completion of a Historic Structures Report for the Arts Building, the Nakashima Foundation for Peace, George Nakashima Woodworker SA, Inc., and the School of Design at the University of Pennsylvania signed a five-year memorandum of understanding to promote George Nakashima "through the study and preservation of the property" (Historic Structures Report, 2013). A complex and interdisciplinary team has been formed to contribute to the project and ensure the future preservation of the building. In 2015, the Getty Conservation Institute awarded a "Keeping It Modern" grant to the University of Pennsylvania to prepare a Conservation Management Plan for the Arts Building and Cloister, to which the project outlined in this report will contribute. To date, a full set of measured drawings and photo-documentation has been completed, a large collection of archival material has been organized in a database, and a comprehensive report about the life and work of George Nakashima has been compiled for the project.

As part of the preservation of the physical structure of the Arts Building, Michael C. Henry, Adjunct Professor of Architecture at the University of Pennsylvania, is consulting with the primary team concerning the building envelope and environmental management. The following report will serve as a conservation perspective that outlines the vulnerabilities and condition risks of the objects within the collection housed in the Arts Building, which will be integrated into the Conservation Management Plan.

In October 2015, the author of this report accompanied Henry and a group of students in his Building Diagnostics and Monitoring course on a visit to the Arts Building. The students were charted with assessing the hygrothermal performance of the building and the condition of the roof deck, and the author completed a basic assessment of the movable contents of the space and noted any preservation vulnerabilities or risks in regards to relative humidity, temperature, and light. In March 2016, a second visit to the Arts Building involved further installing four loggers to monitor the temperature, relative humidity, and light levels, as well as further investigations into the contexts of the collection, their locations within the building, and any risks and vulnerabilities. This second visit also involved taking light levels with and without screens and curtains, and consulting with Mira Nakashima about the collection background and use of the building.

II. Project findings: Materials, Risks, and Data Analysis

General characteristics of the Arts Building

Initial analysis of the space involved identifying general materials present in the collection and inherent characteristics of the building itself that could present a risk to the objects within. The large windows and sliding doors on the south and west walls allow unattenuated daylight to enter the space, which is damaging to all organic materials and especially to textiles and works on paper. Interior soji screens over the windows near the front door on the lower level seemed to reduce light levels significantly. Fluctuations in relative humidity and temperature also seemed to present a moderate risk to the collection, as much of it is comprised of furniture, wooden, and composite objects. It was also noted that the some of the small baskets and other wooden/organic objects within the window-shelving unit on the mezzanine display tide lines and water damage, an apparent effect of condensation forming on the interior windows.

Contents of the collection

The collections within the Arts Building consist primarily of furniture and wooden objects and other organic materials, along with works on paper, metal objects and sculptures, and a small number of textiles (figs. 1-2). Figures 3 and 4 illustrate the general placement of objects within the space, and Table 1 summarizes the contents of the Art Building and briefly outlines the primary risks associated with each category. Time constraints limited the study of the objects in the Arts Building to a general overview and brief investigation into particularly sensitive objects. Table 1 and other discussion of objects in the space are not an inventory or exhaustive list. just represent a general sense of the general contents.

Fig. 1. The upstairs mezzanine with many chairs, a table, and myriad objects on a window-shelving unit

Fig. 2. A representation of the mix of materials in the Arts Building, furniture and other wooden objects, framed works on paper, and metal sculpture

Fig. 3. Diagram of the ground floor of the Arts Building

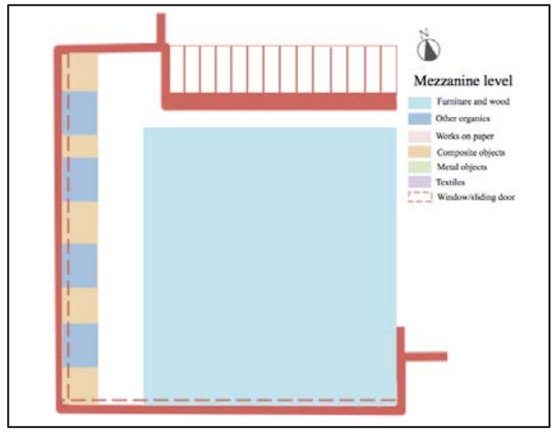
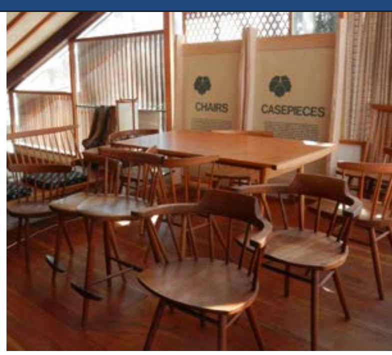


Fig. 4. Diagram of the mezzanine level of the Arts Building

Table 1. Summary of General Categories of Objects in the Arts Building and their Light, RH/Temp Risks

Category of material	Risks	Ideal conditions
 Wood/furniture	Slight sensitivity to fluctuations in RH, can cause warping, cracking Slight sensitivity to light and UV	Most pieces of furniture in the Arts Building have likely been "proofed" or experienced fluctuations They are a medium to low vulnerability to humidity fluctuations: 150 lux 11.24 mW/m^2
 Textiles	Sensitive to light and UV	100 lux 7.7 mW/m^2

 Metals (bronze, iron, brass etc.)	Sensitive to high humidity, not light sensitive	Ideally RH should be kept between 35% and 55%
 Small composite/paper objects	Light sensitive High RH, temperature could cause warping of components	150 lux 11.24 mW/m^2
 Drawings, prints, other works on paper	Light sensitive The sensitivity of the many works on paper in the Arts Center depends on their framing, works with UV-filtering glazing will be much less sensitive than un-framed works (like the scroll shown at left)	50-200 lux 3.75- 15 mW/m^2
 Other composites like clocks, musical instruments	Sensitive to RH fluctuations Slightly to moderately sensitive to light In addition to the wooden furniture, objects comprised of wood in combination with other materials like the mandolin and piano are more sensitive to RH fluctuations because the different materials respond differently to humidity.	Least dramatic fluctuations as possible 100-150 lux 7.7- 1.25 mW/m^2

 Other organics like basketry, leather	Sensitive to light, insect and water damage Some organic materials will fade with light exposure, while other will darken	50-200 lux 3.75- 15 mW/m^2
 Other inorganics like ceramics, glass	Not light sensitive or sensitive to RH or T (unless very extreme) Vulnerable to physical forces, dropping, earthquakes etc.	Because of their lack of sensitivity to light, ceramics and glass objects could be considered as replacement for some of the more sensitive objects in the window shelving

Specific condition issues noted

While most objects seem to be in good condition, a few objects stood out as either unstable or particularly at risk due to their composition or condition:

1. *Lacquer box in SE corner* (fig. 5)
   This lacquer box is currently in very good condition, but Asian lacquer objects are especially sensitive to light damage, at Winterthur they are considered moderately sensitive and are kept at 100 lux. Although the exterior of the box remains in good condition, there is already a marked difference between the interior and exterior, illustrating that light damage has already occurred, and will continue.

Fig. 5. The lacquer box sitting on another wooden box in the south eastern corner, vulnerable to light damage

2. *Ed Fields rug from 1959* (fig. 6)
   There are a few notable textiles in the Arts Building, including an original 1959 Ed Fields rug near the fireplace and a small wall hanging on the mezzanine. Textiles are especially vulnerable to light fading, as ultra-violet and visible light can fade dyes and embrittle fibers. Without knowing exactly the composition of the dyes and fibers, it is difficult to establish lifespan, but in museum settings textiles are generally displayed in short rotations to limit light exposure. The Canadian Conservation Institute suggests three-month rotations for sensitive objects (CCI 2013). The Fields rug was recently stabilized and put on display in

the Arts Building. It is a special example of an original Fields rug that relates to Fields and George Nakashima design collaborations that have only recently been reproduced (Wallis 2015). The rug is currently in beautiful and stable condition, with rich navy blue and bright yellow. The small wall-hanging at the top of the stairs in front of a mezzanine window (fig. 7) exemplifies light damage well, as the side facing the window is a faded light mustard, while the original deep olive green in visible on the opposite side. It is possible though, that with many years of exposure, the fading on the window side has plateaued, and will not worsen significantly. The other side though, is still vulnerable to ambient light, if not as direct as the other side.

Fig. 6. Original Ed Fielding rug near the fireplace

Fig. 7. Hanging textile at the top of the stairs, which is already markedly differently colored on each side

3. *Harry Bertoia sculptures (one spherical (fig. 8) and one "Sonambient" (fig. 9))*
   These two sculptures are particularly important pieces and as metals, are particularly sensitive to high relative humidity. Green corrosion is visible at the tips of the spherical sculpture, which is likely active and serves as evidence of episodes of high relative humidity. There is also visible dust on the other Bertoia sculpture, which can promote corrosion by holding moisture on a metal surface (ASHRAE 2003, 21.2). It would be beneficial to monitor these two sculptures for any further changes in condition.

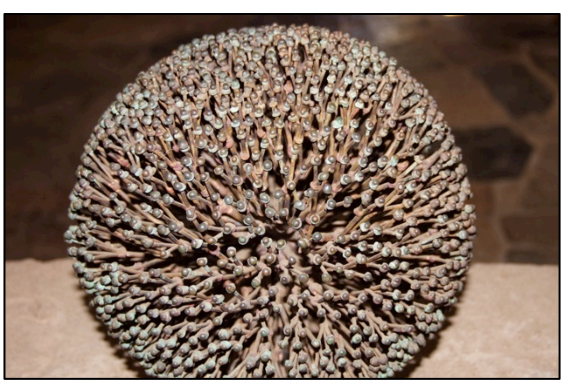


Fig. 8. A spherical Harry Bertoia sculpture with green-white corrosion at ends of nodules

Fig. 9. Second Harry Bertoia sculpture with visible dust accumulation

Analysis of Temperature, Relative Humidity, and Light Data from March 2016

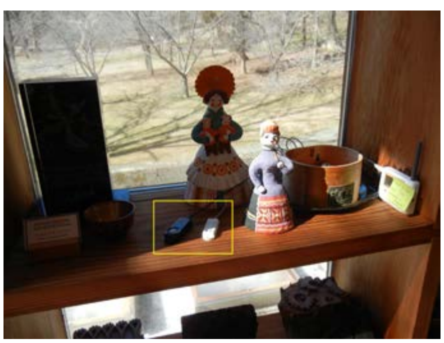
Data was recorded for approximately one month, from March 2, 2016, through early April (loggers deinstalled approximately April 6, 2016 (exact date unsure at this time). Although only one month of environmental data only provides a small window of information about the entire year, this data can help provide insight into relationships between different areas of the building, and we can speculate about other seasonal trends. Summer months will likely be warmer and more humid, while winter months will likely be cooler and drier. It is also possible the winter and summer months will display less fluctuations, as March is a transitional spring month with generally wider more frequent changes in temperature. It will be valuable to continue monitoring the space to gauge these changes.

Figs. 10-15. Location of Data Loggers in Place During the Month of March

Logger H. Near front door on bottom floor, light sensing only (no RH/T)

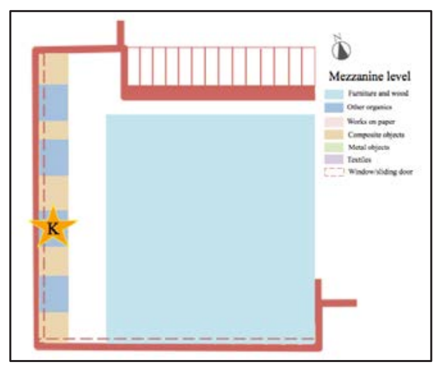
Logger I. Light sensor draped over central drawing, RH/T sensor wedged near bottom edge by heater

Map of the bottom floor showing the locations of loggers I, H, and L



Logger K. Both sensors on the top shelf third column from the left.

Logger L. Both sensors near center of fireplace mantle



Map of the mezzaninie showing the location of logger K

Temperature

As summarized in Table 3, there are no major differences between the highs, lows, and averages of the three loggers. The lows were all about 44 °F, and the averages are all in the mid 60s. The only major outlier was the high temperature recorded in the mezzanine, which was 95.72 degrees. This may be due to a stack effect, heat from the sun penetrating through the surrounding windows, or the proximity of a baseboard heater. It was noted during both visits that it felt quite warm on the mezzanine, so these results were not surprising. Comparing the temperature graphs for all three loggers shows that there were dramatic daily fluctuations in temperature on the mezzanine, while the smallest fluctuations were recorded on the fireplace mantle. This may be due to the buffering effects of the stone mantle. The large, dramatic fluctuations in the mezzanine are likely due to exterior air infiltrating the surrounding windows, making the space more sensitive to exterior fluctuations. The fluctuations recorded on the frame were in between those of the mezzanine and fireplace. Overall the same broad patterns are visible, with larger fluctuations occurring over about 3-6 days.

Table 2. High, low and average temperature logged from March 2016 (degrees Fahrenheit)

Location	High	Low	Average
Frame (I)	76.64	44.60	63.29
Fireplace (L)	77.00	44.96	63.12
Mezzanine (K)	95.72	44.06	66.00
Overall Average	83.12	44.54	64.14

Relative Humidity

Relative humidity recorded by the three loggers displays similar patterns as temperature. There is a strong inverse relationship overall between RH and temperature, strongest on the mezzanine. The highs in humidity are with 2% of each other, and both the frame and fireplace shared a low of 23%, while the low on the mezzanine was 14%, which relates to the abnormal high in temperature. The overall average relative humidity was 49.17%. All loggers recorded similar fluctuations as temperature, with the mezzanine recording the most dramatic, the fireplace the smallest, and the frame between the two. The most dramatic overall fluctuations are visible the last few days of March, when there is a 40% change in humidity over 2-3 days.

Table 3. High, low, and average relative humidity logged March 2016 (% RH)

Location	High	Low	Average
Frame (I)	66.00	23.00	44.44
Fireplace (L)	64.00	23.00	43.32
Mezzanine (K)	64.00	14.00	39.98
Overall Average	69.00	27.32	49.17

Light

Light levels recorded by three of the four loggers were extremely high, while the logger near the front door was relatively much lower, and recorded no UV. This is due to the soji screens that cover the window and three skylights. Generally, for a partially controlled environment light levels are recommended to be 200-lux visible light and $15 mW/m^2$ UV (Michalski 1997, 2). For comparison, Winterthur suggests 200 lux for its least light sensitive objects (see Table 6 in the appendix for Winterthur's guidelines). The majority of the light recorded at the Arts Center is related to daylight, so there is very little to no light exposure after sundown, which is a perk of day-lighting.

Table 4 shows the highs, lows, averages, sum, and extrapolated annual sum for all four loggers. At the front door, the average visible light reading was 7.54 lux, which is quite low. The average at the fireplace logger is the next lowest, with an average of 207.71 lux, the average recorded at the frame was 271.56, and at the mezzanine was a massive 1,135 lux. Seasonal changes in sun's position would likely influence the light recorded by the loggers at other points in the year, but to gain insight into light levels overall, each sum was divided by 35 then multiplied by 365 to estimate a annual lux hour total. All except the front door logger totaled huge lux hours, much over the ideal 730,000-lux hours if 200 lux was maintained all year.

Interestingly, looking at the graphs recorded by the loggers, the light levels in the mezzanine are very high and then drop off dramatically after March 12th (see appendix). This is a phenomena witnessed at Winterthur as well, and is likely related to seasonal positions of the sun (Peirce 2016).

Table 4. Light logged March 2016 (ultra-violet in mW/m^2, visible light in lux)
A maximum **200**-lux **is recommended**, with **15 mW/m^2 UV**, for a total of **730,000-lux hours annually**

Location	High		Low		Average		Sum (for ~35 days)		Sum (1 year est.)
	UV	Vis	UV	Vis	UV	Vis	UV	Vis	Vis
Front door (H)	0.00	201.3	0.00	0.00	0.00	7.54	0.00	7,215.5	71,179
Frame (I)	2,140	45,480.0	0.00	0.00	16	271.56	15,085	259,810	2,562,990
Fireplace (L)	680	15,740.0	0.00	0.00	9	207.71	8,972	198,770	1,960,839
Mezzanine (K)	3,520	33,630.0	0.00	0.00	191	1,135.4	183,100	1,088,800	10,740,865
Overall Average	370	23,762.83	0.00	0.00	54	405.55	51,789	388,648.88	3,833,969

During the second site visit, light levels were recorded in three places throughout the building with and without soji screens, and in one place, with and without curtains. Table 5 summarizes these findings, which show that both screens and curtain drastically reduce light infiltration, which is also demonstrated by the low light levels near the front door.

Table 5. Testing light levels with and without screens in three places:
Taken about 1:15pm on 3/2/2016, a clear, sunny day
A maximum **200**-lux **is recommended**, with **15 mW/m^2 UV**

Location	Ultra Violet Light (mW/m^2)			Visible Light (lux)		
	Without screen	With screen	Difference	Without Screen	With screen	Difference
Front sliding door in direct sun, partially diffused by trees outside	8,100-11,000	190-220	~9,345	17,000-23,000	1000-1300	~8,850

Back window by fireplace in indirect sun	2274	258	2,016	990	319	671
Upstairs sliding door in direct sun	17,000	930-960	~16,055	34,000	3,850	30,150
Upstairs sliding door in direct sun with curtains pulled instead of soji screens	17,000	500-480	~16,510	34,000	1230-1250	~32,760

III. Suggestions to mitigate risks to objects

Light

There are many ways to mitigate daylight, from simple to complex. It would be beneficial to pull all curtains as much as possible, which as indicated by Table 5, is a very effective light mitigation step. The soji screens are also effective means to diffuse light, so installing the screens present in the mezzanine would be very helpful. The manufacture of more screens may also be an option, which could even be temporarily installed. Soji screen in the window shelving may also protect the objects from damage from condensation.

In addition to these physical light barriers, the installation of light-filtering window films in highly suggested. There are many films currently on the market with a range of protection. Some filter only ultra-violet light, while some also filter some visible light. Some can change the color of light slightly, so it is important to consider aesthetic choices as well (Boye et al. 2010, 14).

Mitigating light damage will go a long way in lengthening the lives of the objects in the Arts Building. If some of these options are not possible to reduce light exposure, it is also suggested to rotate light sensitive objects, or even move them permanently. It is possible that some objects from the window shelving could be moved down near the front door, and some of the least light sensitive objects from the door area (like ceramics, glass, and wood-working tools) could be moved to the mezzanine.

Relative Humidity and Temperature

Wooden artifacts and furniture

Original George Nakashima furniture comprises a large quantity of the objects within the Arts Building. There are also many large slabs of raw wood and other small wooden objects like baskets and textile printing blocks. Furniture and wooden objects are especially sensitive to fluctuations in relative humidity (RH), and expansion and contraction can cause warping and cracking (Camuffo et al. 2014, 27). An important concept for this space though, is the idea of proofed RH, which Stefan Michalski explains as "The largest RH or T fluctuation to which the object has been exposed in the past or, alternatively, just the lower and highest RH and T of the past" (Michalski 2007, 11). For the furniture and wooden objects in the collection to remain stable in this environment, relative humidity extremes should be kept within those already experienced by the object. It is assumed that any modifications to the HVAC system would only tighten the control and fluctuations; and the furniture and wooden objects in the Building have likely already experienced any future fluctuations caused by the exterior climate.

Humidity sensitive objects: metals

Although fluctuations may not pose a major threat to the wooden artifacts in the collection, metal objects like the Harry Bertoia sculptures and other small metal artifacts are sensitive to high levels of relative humidity. 35%-55% is generally suggested to prevent corrosion on metal objects (Logan and Selwyn 2007).

Other suggestions to promote the preservation of the collection:

Housekeeping:

Establish a general housekeeping plan that includes regular dusting of collection objects to prevent dust accumulation, which can hold moisture on the surface of an object, attract pests, abrade surfaces, and be visually disruptive. Although the space appeared very clean and tidy, it would be beneficial to ensure a housekeeping plan is undertaken to ensure floors are clean of any food, dirt, or debris from outside to discourage pest activity.

Pest management:

Three potted plants were noted on the second visit; raw wood for the fireplace, and crumbs of food could all harbor or attract pests, which could then damage textiles, paper, and other organic materials. The pragmatic useful nature of the Arts Building means eliminating these activities would be impractical, but it would be beneficial to enact a pest monitoring protocol with a few pest traps strategically placed and checked every month or two to prevent any infestation that could detrimentally damage the collection.

Dissociation:

It would be beneficial to establish an inventory of the objects in the Arts Building, especially the many small objects on the mezzanine window shelving, most of which seem to have been separated from their labels. An inventory could facilitate easier evaluation of the objects, their condition, and location within the Building. An email conversation with Pan Sergey of the James A. Michener Museum revealed that an inventory previously thought completed of all the objects in the Building actually only contains archival materials donated to the Museum: "The only inventory I created is of paper materials (correspondence, photographs, publicity materials, and a few original drawings) which were contained in flat files and vertical file cabinets in the Arts Building, or boxes in the Cloister Room, and transferred to the Michener archives" (Sergey 2016).

Archival documents within the flat file:

A further investigation into the temperature and humidity within the flat file cabinet could be beneficial, as it is situated over a heated floor, which has unknown effects on heat and moisture buildup within the cabinet.

Ben Shahn Mosaic on exterior of Building:

The mosaic on the West exterior wall of the Arts Building appears to be in good condition, while only a basic visual assessment was performed during the two site visits. The slight outward slope has ensured water does not settle on the mosaic, which would have eroded the tesserae and substrate over time. There are various lost tesserae, and an area of dark grime and biogrowth at the middle of the bottom edge of the mosaic, where water has dripped off the roof and splashed on a large square stone and onto the mosaic. The removal of this stone would remediate this issue. It would also to be valuable to monitor more closely for the continued loss of tesserae to ensure no water is infiltrating behind and compromising the substrate.

Fig. 16. An overall view of the Ben Shahn mosaic on the exterior of the Arts Building

Fig. 17. A lost tessera over a screw

Fig. 18. An area of lost tesserae

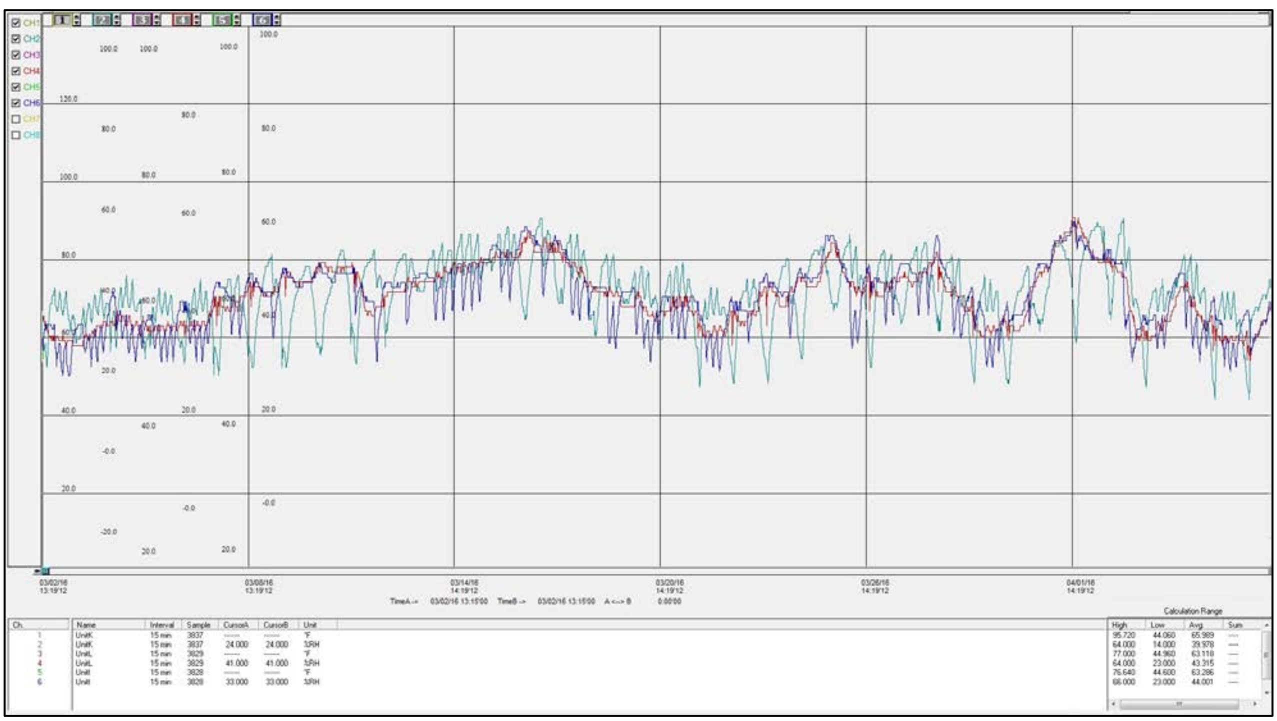
Fig. 19. Area of biological growth where water drips and splashes off of a stone onto the mosaic, promoting mold and other bio growth

IV. Appendix:

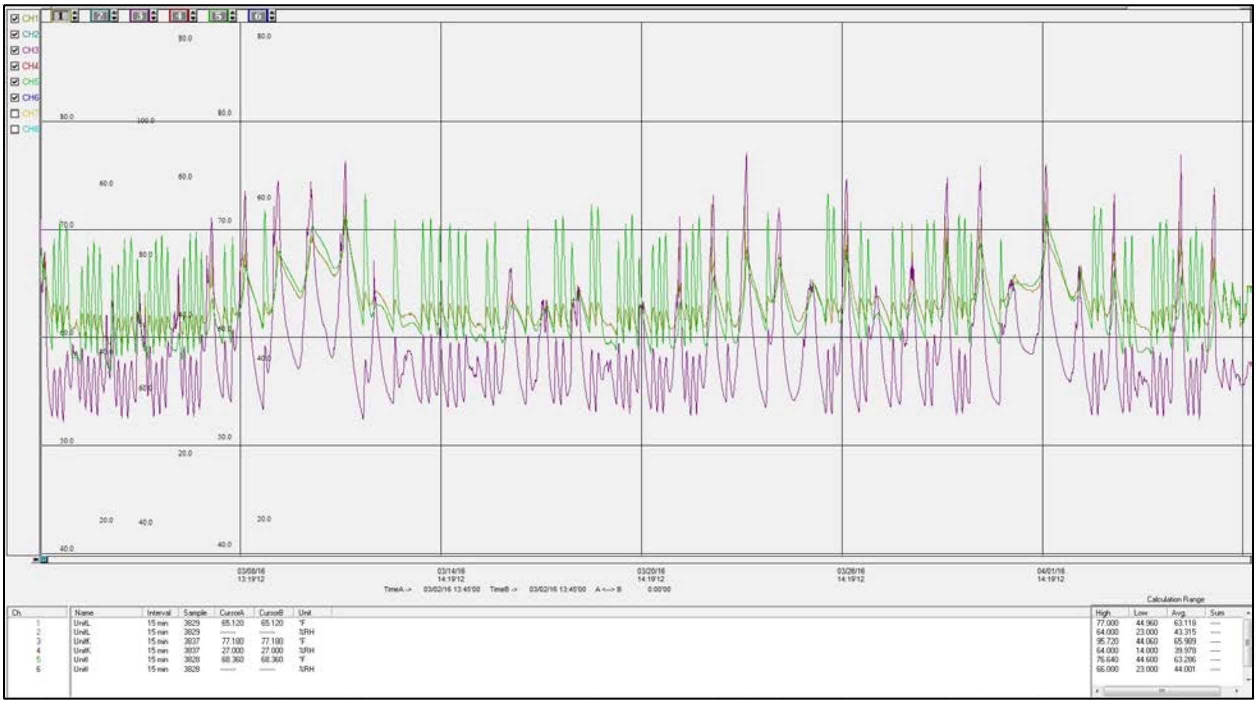
Table 6. Recommended Light Levels at Winterthur

Sensitivity	Visible Light (Lux)	Lux hours annually	UV (mW/m^2)
Sensitive: Other textiles and paper; sensitive organic materials and pigments/media	50 lux	180,000 lux hours *(50 lux x 10 hours x 365 days)*	3.75 mW/m^2
Moderately sensitive: Asian lacquer; other organic materials.	100 lux	365,000 lux hours *(100 lux x 10 hours x 365 days)*	7.5 mW/m^2
Slightly sensitive: Paintings (oil, egg tempera, acrylics), furniture, objects with painted surfaces	150 lux	545,000 lux hours *(150 lux x 10 hours x 365 days)*	11.25 mW/m^2
Least sensitive: metals, stone, glass, enamels, ceramics	200 lux	730,000 lux hours *(200 lux x 10 hours x 365 days)*	15 mW/m^2

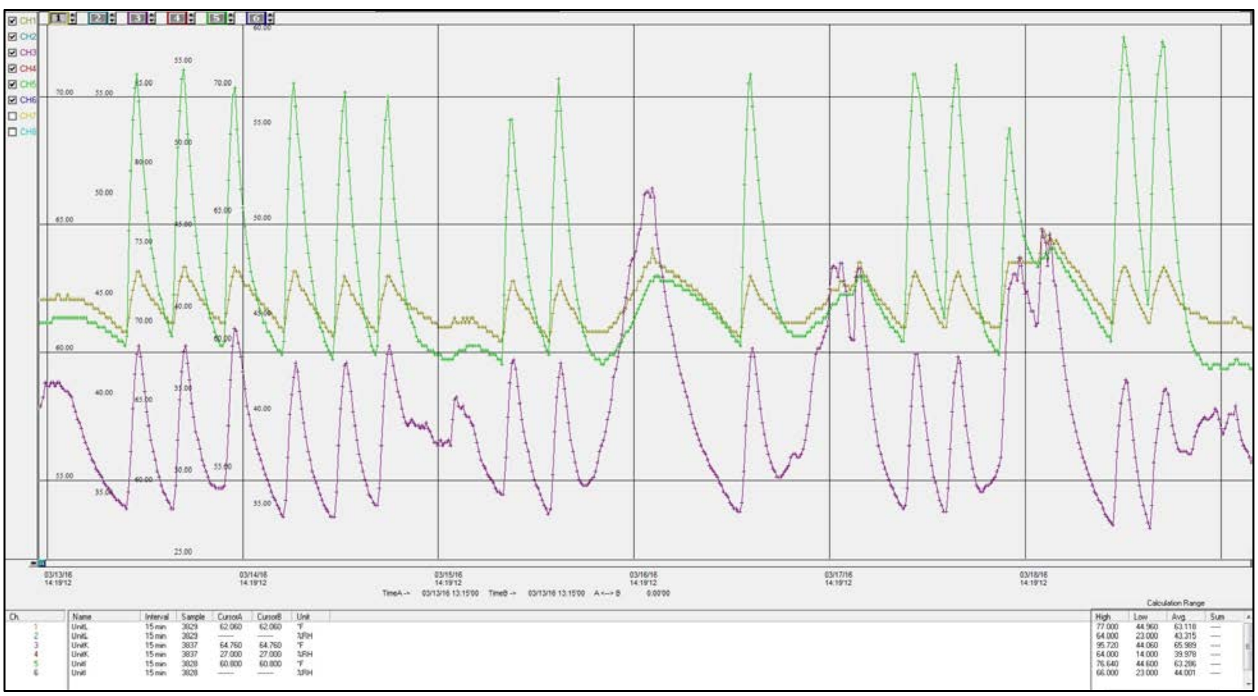
Temperature and Relative Humidity Data



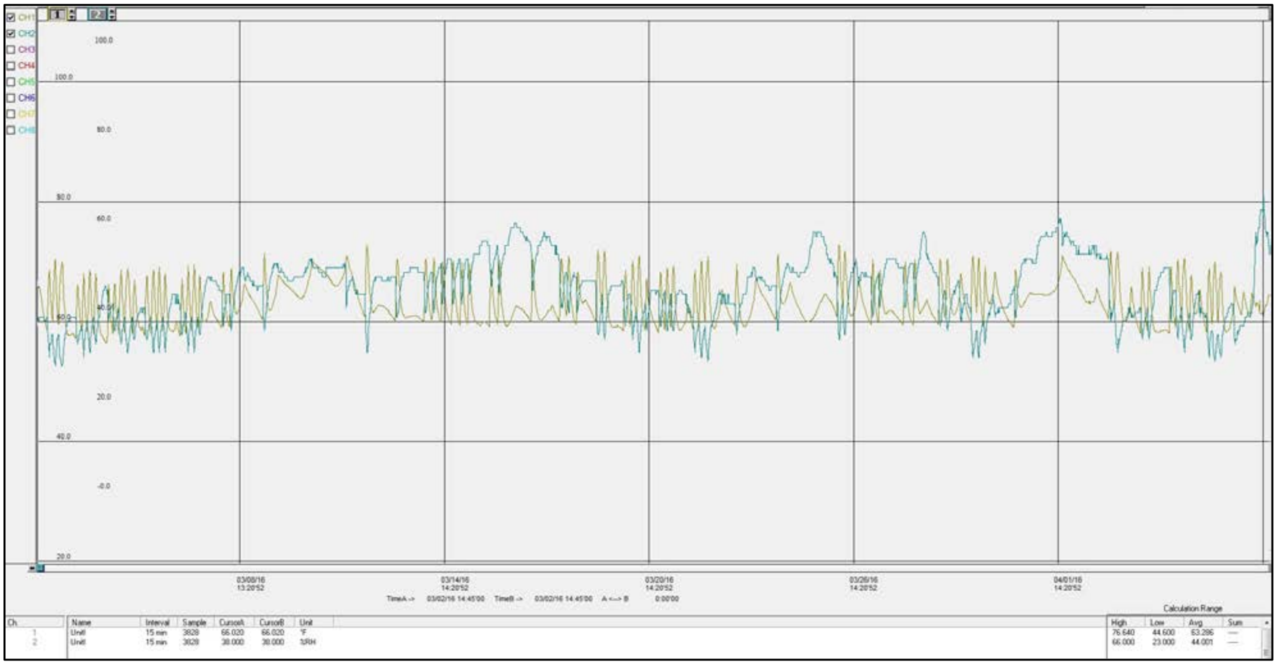
Relative humidity during the month of March for all three RH-recording loggers: the mezzanine (K), fireplace (L), and frame (I). Shows the tightness of fluctuations on the fireplace (in red) relative to the large fluctuations on the mezzanine (in teal). The severity of fluctuations near the frame (in purple) are somewhere between the other two. The overall average relative humidity was 43%.



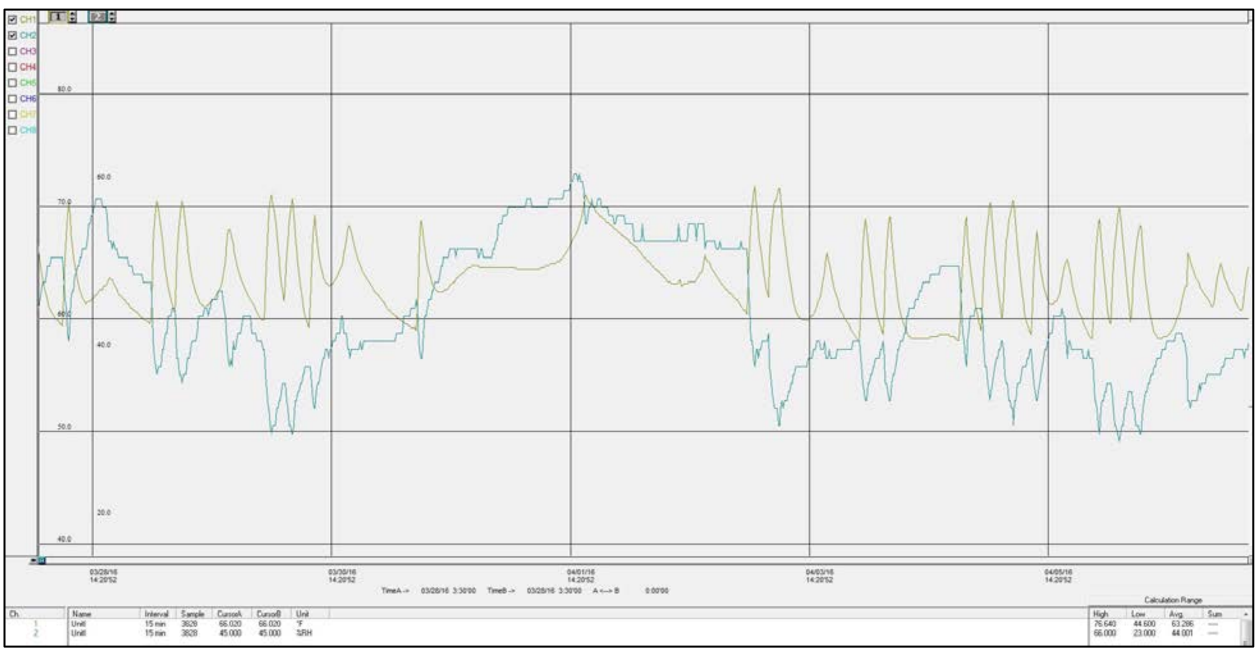
Temperature during the month of March for all three RH-logging loggers.



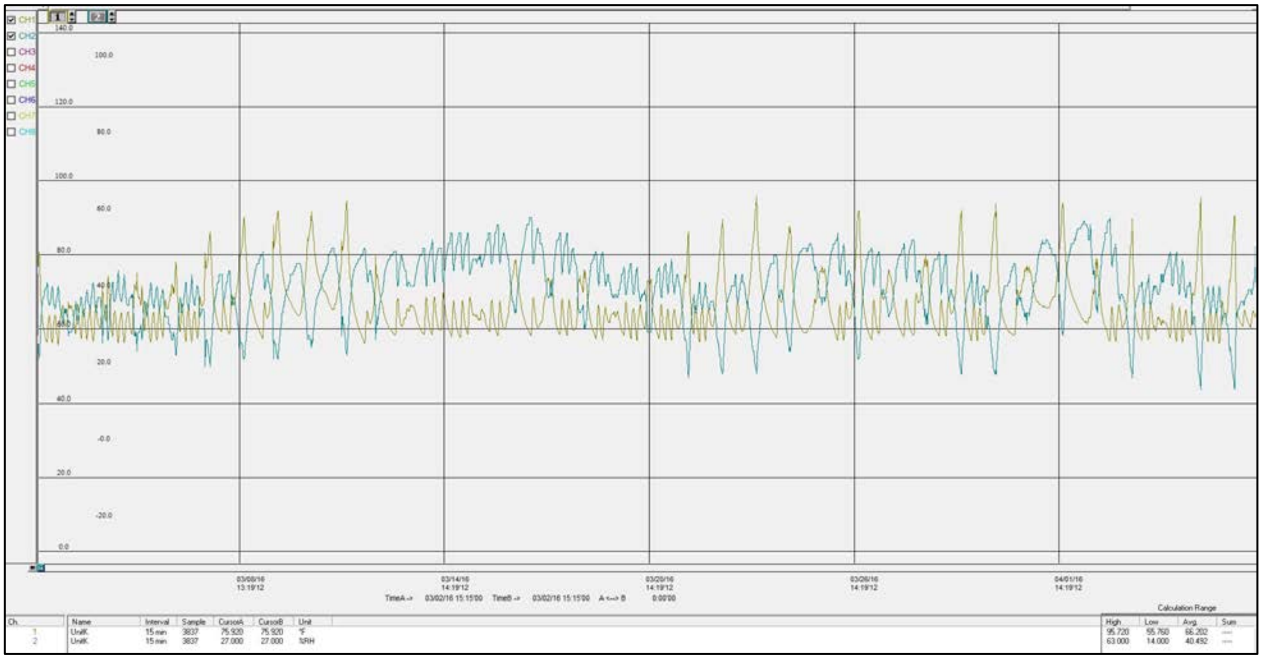
This graph shows approximately six days of temperature data from 3/13-3/18 for all three of the temperature-recording loggers. The logger at the center frame (green) was overall higher in temperature than the other two locations, but the mezzanine (purple) recorded the highest single temperatures and had the largest fluctuations overall while recording generally lower temperatures. The large peak recorded on the mezzanine between 3/15 and 3/16 may be related to the heat being turned on. The logger on the fireplace mantle (yellow) recorded the smallest fluctuations overall.



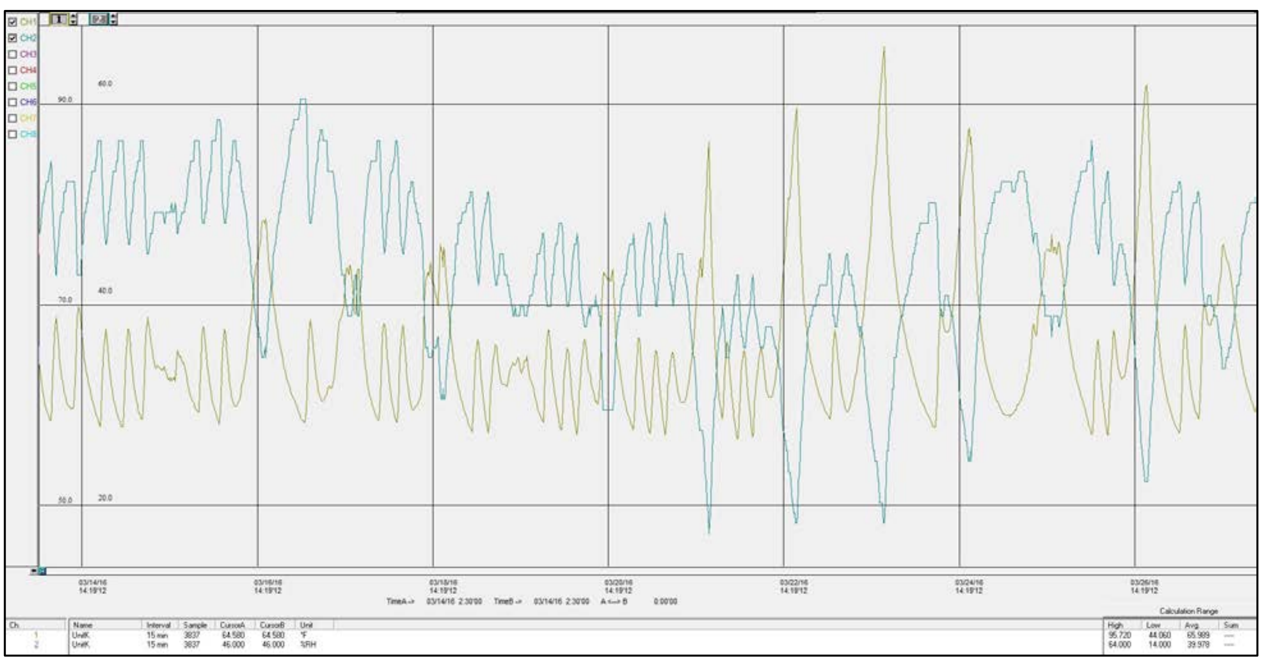
Overall temp and RH for the frame logger (I). (RH blue, temp yellow).



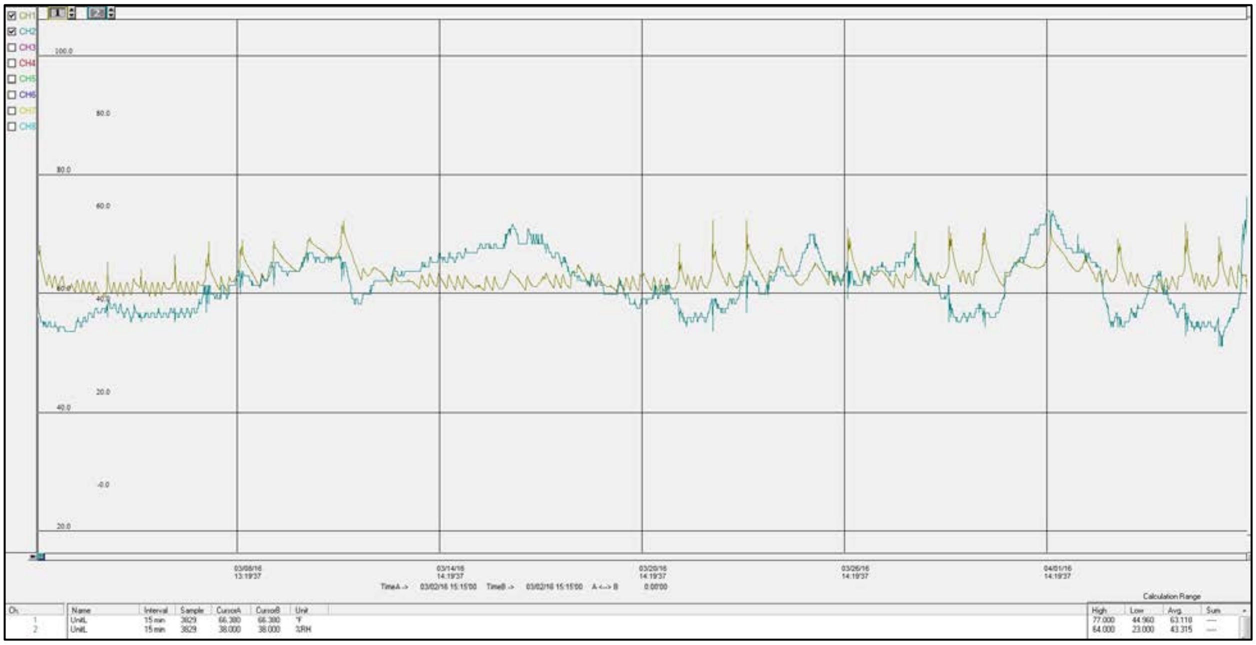
Detail temp and RH for the frame logger (I) from about 3/28-4/7, when one of the largest fluctuations in RH occurred. (RH blue, temp yellow).



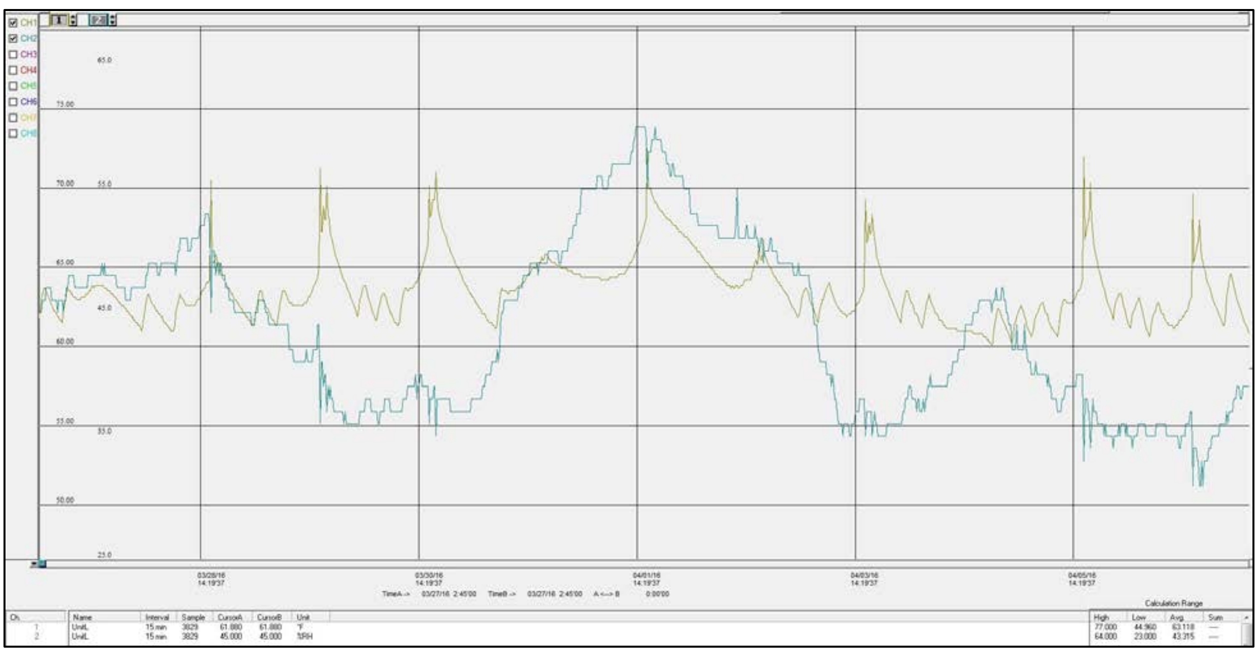
Overall temp and RH data from the mezzanine logger (K) (temp yellow, blue RH).



Detail of temp and RH data from the mezzanine logger (K) from about 3/14/-3/26 (temp yellow, blue RH), showing the strong inverse relationship between RH and temp, and the sharp daily fluctuations.

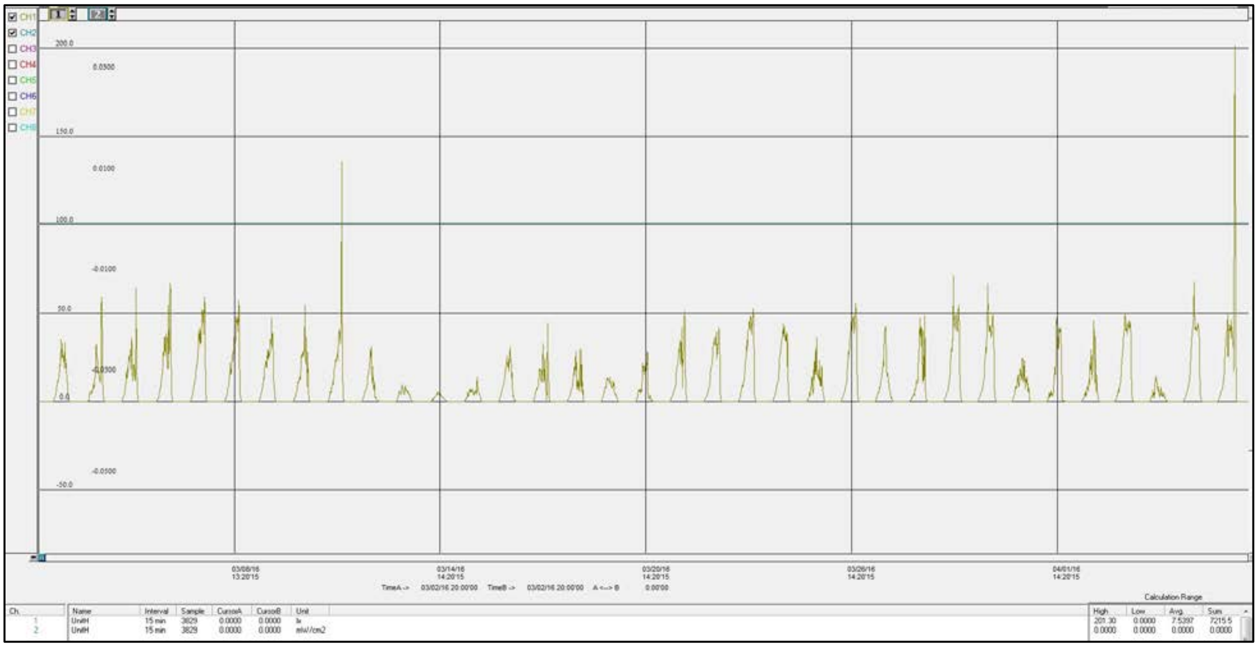


Overall temp and RH data from the fireplace logger (L) (temp yellow, blue RH), showing relatively shallow fluctuations.

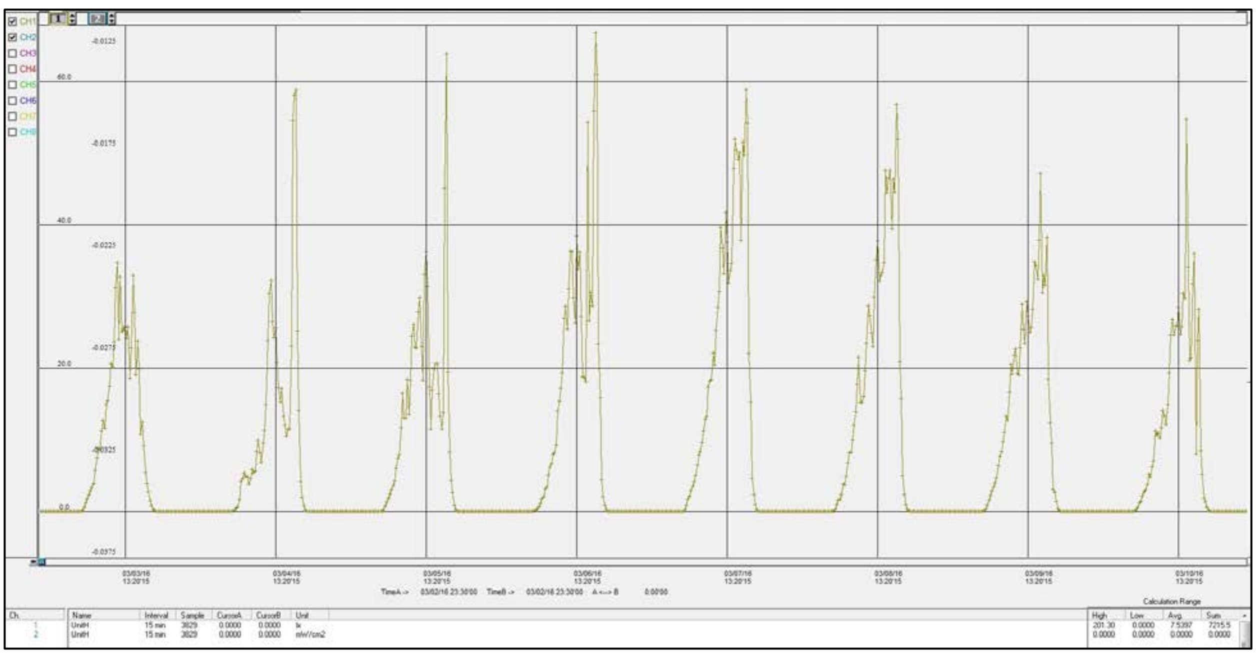


Detail temp and RH data from the fireplace logger (L) from about 3/27- 4/5 (temp yellow, blue RH).

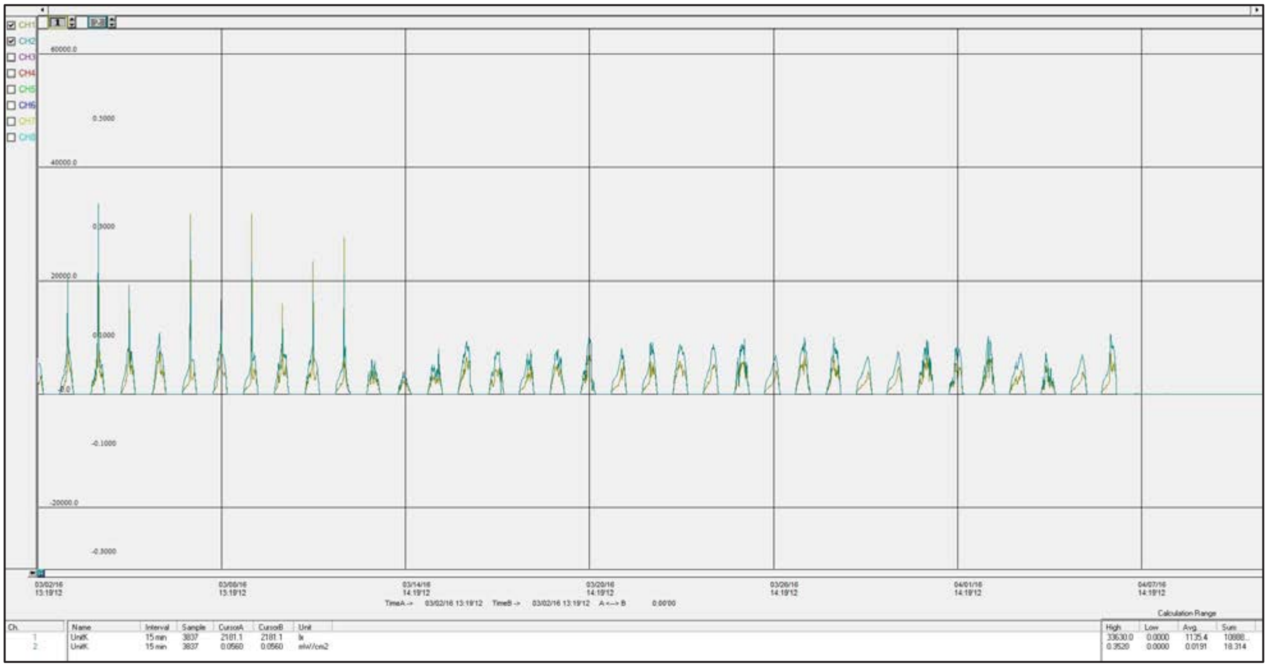
Light Data



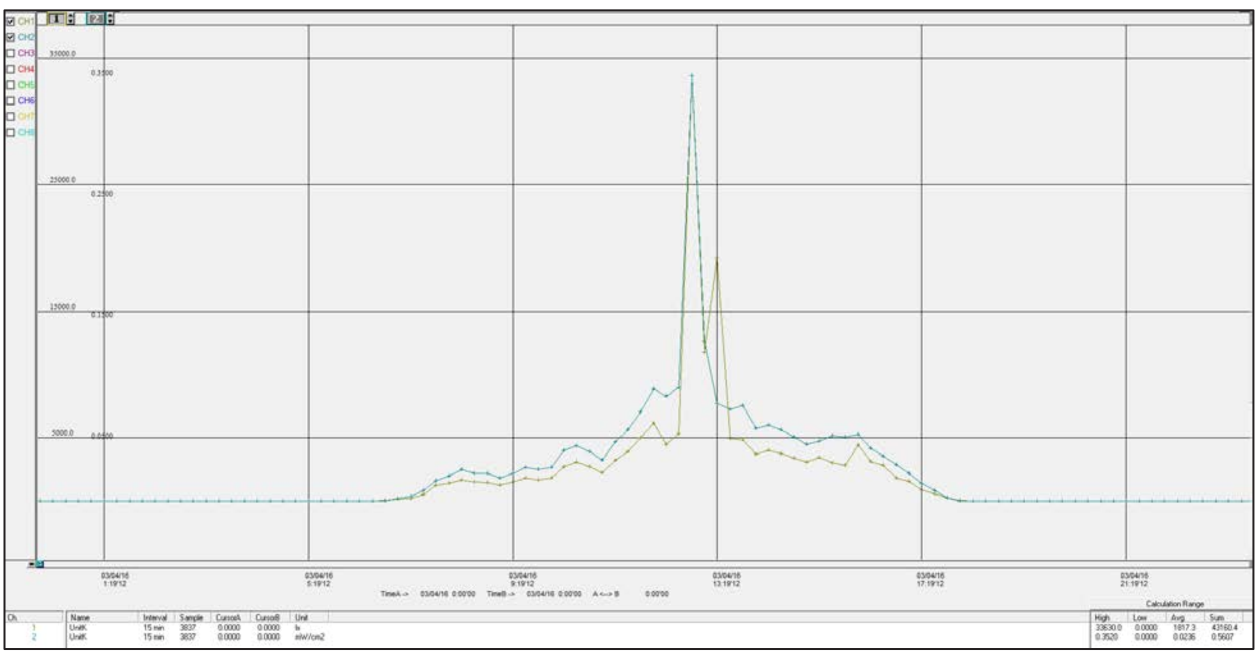
Overall light data from the door logger (H) showing that there is no ultra-violet radiation detected in this area.



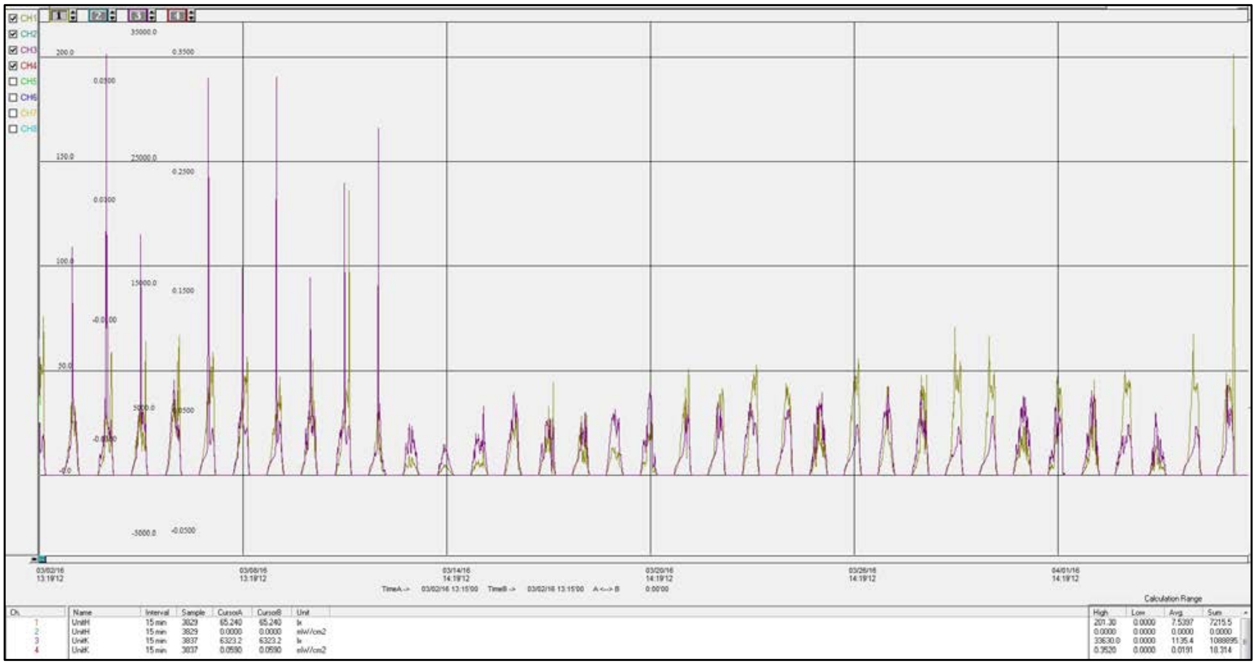
Detail of light data from the door logger (H) from about 3/2-3/10, showing a slight late-afternoon peak in visible light.



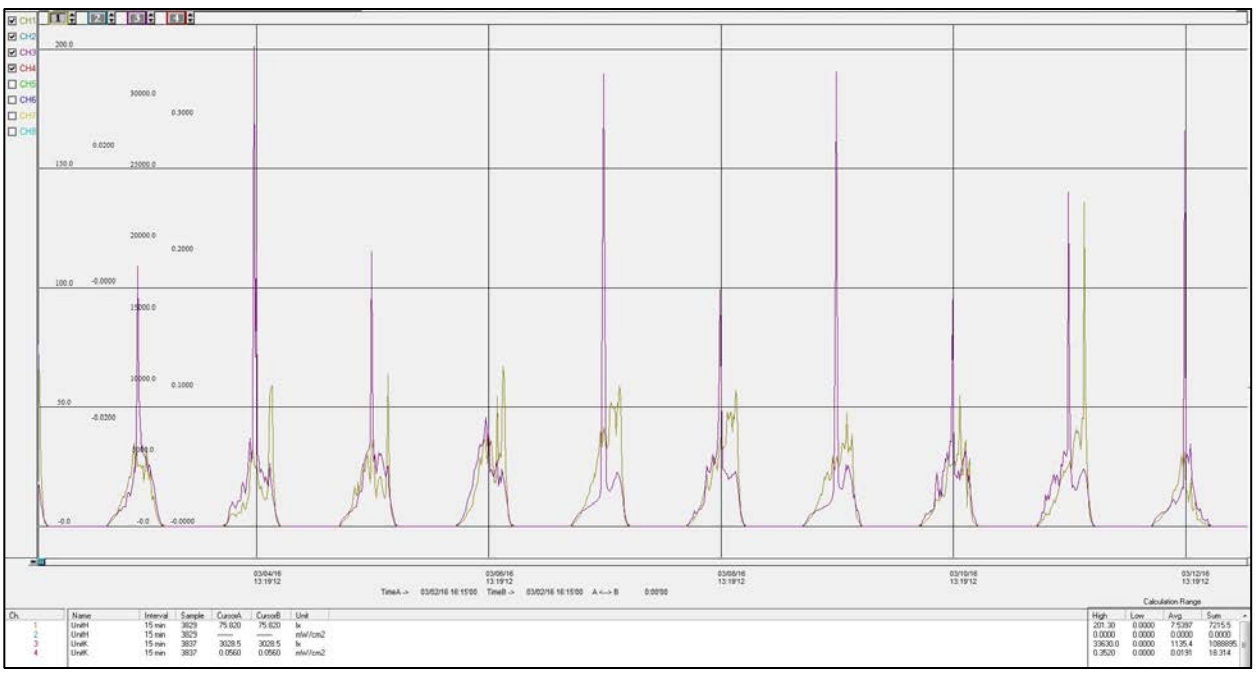
Overall light data from the mezzanine logger (K), showing the interesting drop-off of high peaks after approximately 3/12 that is likely due to a seasonal shift.



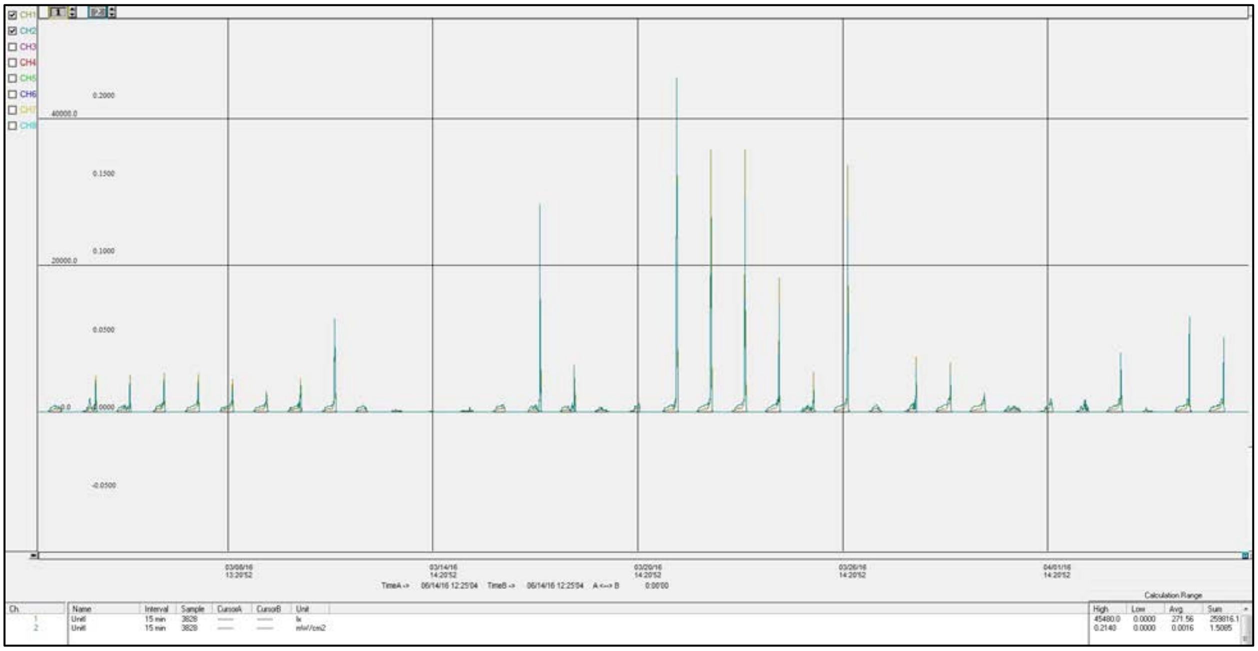
Detail of light data from the mezzanine logger (K), showing all day of 3/4, showing a peak around noon.



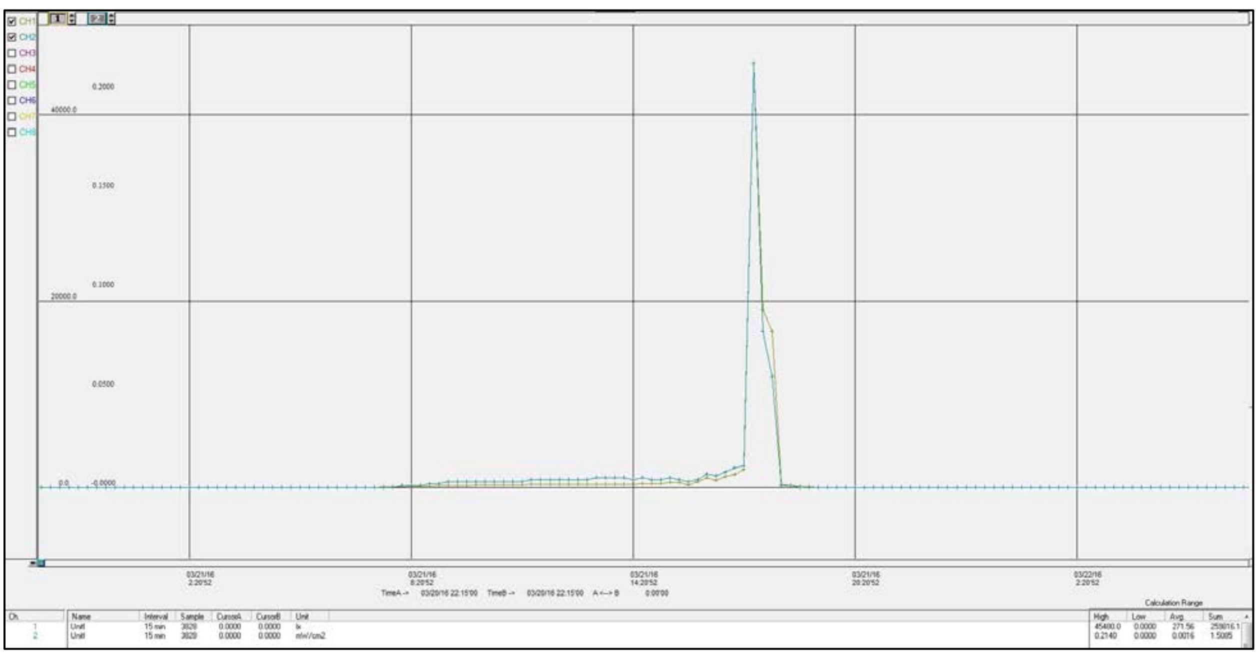
Overall visible light data overlaid from the door (yellow) and mezzanine (purple) loggers.



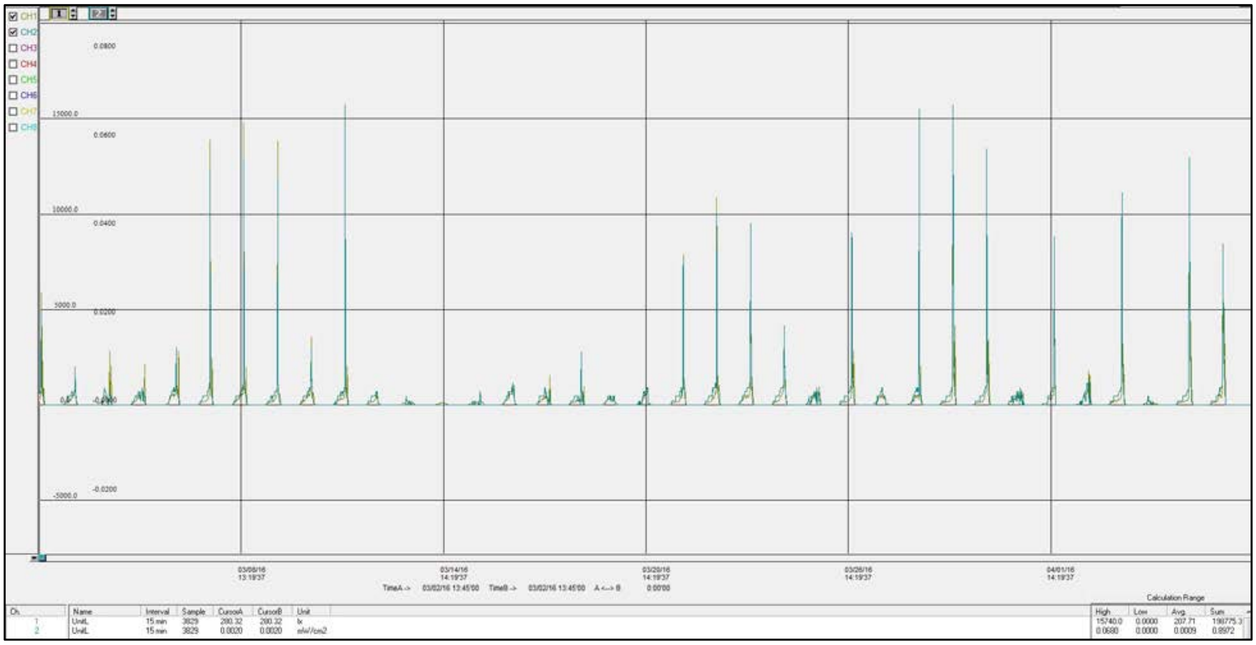
Detail of visible light data overlaid from the door (yellow) and mezzanine (purple) loggers from about 3/2 to 3/12.



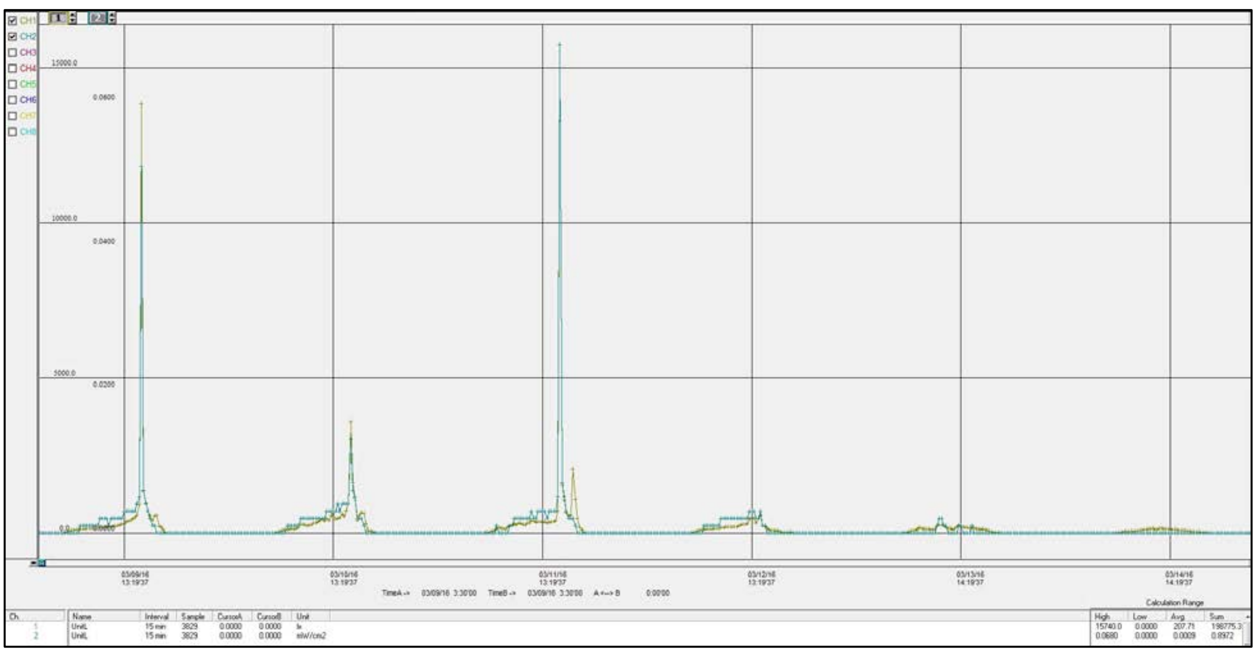
Overall visible and UV light data from the frame logger (I), showing some large peaks mid-month on 3/21-3/24 and 3/26. 3/21 was snowy, while 3/22-3/24 and 3/26 were clear and sunny.



One-day of visible and UV light data from the frame logger (I) on 3/21, the peak is about 5pm.



Overall visible and UV light data from the fireplace logger (L).



Detail of visible and UV light data from the fireplace logger (L).

Partially Annotated Bibliography

General Environmental Control of Cultural Heritage Collections

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2003. *Chapter 21: Museums and Libraries, ASHRAE Handbook*. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers.

- The ASHRAE Chapter 21 concerning cultural heritage collections is a useful basic reading for all preventive conservators and anyone involved in collections management, and is a concise review of basic preventive concepts. It is a good resource for anyone that works in a collaborative environment with building managers and engineers as it uses concise and clear language that is easy to understand. It outlines major agents of deterioration that relate to the building engineering, their general effects on cultural heritage objects.

Bickersteth, J. 2014. "Environmental conditions for safeguarding collections: What should our set points be?" *Studies in Conservation.* 59 (4): 218-224.

Henry, M. 2001. Materials in museum buildings and collections: Technical note. http://extranet.getty.edu/gci/teaching/downloads/MaterialsInMuseums.TN.pdf

Huijbregts, Z, M. Martens, J. van Schijndel, and H. Schellen. 2015. The use of computer simulation models to evaluate the risks of damage to objects exposed to varying indoor climate conditions in the past, present, and future. *Climate for collections: standards and uncertainties*. London, United Kingdom: 375-387.

- This article is complex and dense, but explains well the potential of modeling climate conditions within a historic structure as well as modeling heat and moisture induced strain of a specific object, in this case a wooden cabinet from 1690-1710 within Amerongen Castle, a 17th century castle in the Netherlands. The research looks to pinpoint the appropriate limits of RH and temperature fluctuations for the cabinet and to gauge the potential damage caused by a newly installed heating system in the castle. The authors distill the overwhelming computer calculations involved in modeling into manageable explanations that make the process seem doable for other institutions. They provide graphs that compare gathered climate data with computer modeling to demonstrate the accuracy of the process. This is a great resource for anyone interested in the effects of RH on collections and the great potential of computer modeling in museums and historic houses.

Mecklenburg, M. F., and C. S. Tumosa. 1999. Temperature and relative humidity effects on the mechanical and chemical stability of collections. *ASHRAE Journal* 41(4): 77-83.

Michalski, S. 1994. Relative humidity and temperature guidelines: What's happening? *Canadian Conservation Institute Newsletter,* No 14: 6-10.

Michalski, Stefan. 1996. "Quantified Risk Reduction in the Humidity Dilemma". *APT Bulletin.* 27 (3): 25-29.

- This is a brief yet pithy article that outlines issues and mechanics of humidity fluctuations and the effects on building envelope and wooden artifacts. Michalski discusses seasonal wall condensation and the importance of understanding geographical climate differences. He also explains the influence of stack effect and the building skin. Briefly discussed as well are the risks associated with humidity fluctuations on wooden artifacts and furniture. He provides a summary chart that outlines objects of low to high vulnerability based on joinery techniques and construction, as well as discusses the influence of reaction time and stress relaxation. This article is in no way comprehensive, but is a good starting point for anyone considering the effects of relative humidity fluctuations on building and wooden artifacts.

Thickett, D, L. Cséfalvayová, and M. Strlič. 2011. Smart conservation: targeting controlled environments to improve sustainability. *ICOM-CC 16th triennial conference.* Lisbon, Portugal: 19-23.

Environmental Control of Historic Buildings

Camuffo, D., and G. Sturaro. 2002. Church heating: A challenge looking for solutions. *Research for Protection, Conservation and Enhancement of Cultural Heritage: Opportunities for European Enterprises*. Luxembourg: European Commission: 128–36. <ftp://ftp.cordis.europa.eu/pub/eesd/docs/ka4_protection_conservation_enhancement.pdf>

Kerschner, R.L. 2008. Providing safe and practical environments for cultural property in historic buildings… and beyond. *Getty Conservation Institute: Contribution to the Experts' Roundtable on Sustainable Climate Management Strategies.* Tenerife, Spain. http://www.ischool.utexas.edu/kilgarlin/gaga/proceedings.html

Michalski, S. 1998. Climate control priorities and solutions for collections in historic buildings. *Historic Preservation Forum* 12(4): 8-14.

Thickett, D., L. N. Luxford, and P. Lankester. 2012. Environmental management challenges and strategies in historic houses. *The artifact, its context and their narrative: Multidisciplinary conservation in historic house museums.* The Joint Conference of ICOM-DEMHIST and three ICOM-CC Working Groups. Los Angeles: the Getty Research Institute.

- This is a brief overview of challenges historic houses face in regards to preventive conservation and particularly environmental control and management. It discusses some unique solutions to these challenges enacted by historic houses in the United Kingdom. The article focuses on relative humidity and temperature, light, and acoustic emissions. It presents case studies complete with graphs and figures that illustrate the issues that can arise when conservators have to balance the needs of old and historic buildings and composite collections.

Winterthur Preventive Team. 2014. Updated Environmental Guidelines Handout. Winterthur Museum and Country Estate, Winterthur, DE.

Risk Assessment and Management

McCubbin, M, A. Cannon, C. Carter, D. Henry, H. Privett, N. Ladas, D. Leggett, R. Leveson, M. Raberts, L. Stedman, and R. Waller. Improving risk assessment methods in a complex setting: Museum Victoria's collection risk assessment. *ICOM Committee for Conservation preprints.* 17th Triennial Meeting, Melbourne. Paris: ICOM. 15-19.

Michalski, S. 1996. Environmental guidelines: Defining norms for large and varied collections. Paper presented at the workshop *Preservation of collections: assessment, evaluation, and mitigation strategies,* Norfolk, Virginia. Washington DC: AIC. 28-33.

Michalski, S. 2007. The ideal climate, risk management, the AHRAE chapter, proofed fluctuations, and toward a full risk management. Contribution to the Experts' Roundtable on Sustainable Climate Management Strategies. Getty Conservation Institute.

- In this paper Michalski discusses the past, present, and future of the ASHRAE chapter 21 about environmental management in museums and how it can be used by conservators and museum professionals to develop a risk management approach to climate control. Michalski focuses on the development of and characteristics of the AA, A, B, C, and D ratings established in the newest ASHRAE chapter and how these rating can be used to evaluate collection risks, instead of establishing an "ideal." He also discusses the idea of proofed RH, its benefits, as well as some complications like fatigue and stress. This is a valuable introduction to risk management in conversational language that is easy to understand.

Michalski, S. 2015. "Tools for assessing needs and impacts". *Studies in Conservation.* 60 (S2): S2-23-S2-31.

Staniforth, S. Conservation heating to slow conservation: A tale of the appropriate rather than the ideal. *Getty Conservation Institute: Contribution to the Experts' Roundtable on Sustainable Climate Management Strategies.* Tenerife, Spain.

- This article was written for members of IIC and discusses philosophically the present state of environmental management in museums in a historical context. The article is a valuable reality check for anyone invested in preventive conservation, it looks to predict what the future of environmental management will look like, and is particularly focused on a global perspective that considers climate change and sustainability. Staniforth also discusses leadership and the need for conservators and preservation-minded individuals to gain leadership skills that will help them achieve higher positions in cultural

institutions. This article is a manifesto that outlines what the conservation field needs to achieve in the next 35 years.

Preventive Conservation of Specific Materials

Canadian Conservation Institute Textile Lab. 2013. Textiles and the environment. Canadian Conservation Institute (CCI) Notes 13/1. Minister of Public Works and Government Services, Canada. < http://canada.pch.gc.ca/eng/1439925170741>

Camuffo, D.; C. Bertolin, A. Bonazzi, F. Campana, and C. Merlo. 2014. "Past, present and future effects of climate change on a wooden inlay bookcase cabinet: A new methodology inspired by the novel European Standard EN 15757:2010". *Journal of Cultural Heritage.* 15 (1): 26-35.

- This article explores ways to reconstruct the past climactic experience of objects, which would provide information used to establish best conditions. The article uses one particularly vulnerable object, a 1477 wooden inlay bookcase to illustrate these methods. The authors discuss how historic climate data, or "proxy data" is compiled. This is an interesting article that looks to more accurately establish a protocol for quantifying the idea of proofed RH or temperature. The methodology is interesting but not efficient or especially relevant to the preventive workings of most museums as it is time consuming, mathematically cumbersome, and requires detailed knowledge of an objects provenance. The article does however, represent a valuable case study of an object with such a well-known provenance, and it exemplifies proofed RH, and how conservation treatment can "reset" proofing.

Logan, J, and L. Selwyn. 2007. The storage of metals. Canadian Conservation Institute (CCI) Notes 9/2. Minister of Public Works and Government Services, Canada. <http://canada.pch.gc.ca/eng/1439925170350>

Lighting

Boye, C., F. Preusser, and T. Schaeffer. 2010. UV-blocking window films for use in museums--revisited. *Newsletter (Western Association for Art Conservation)* 32, no. 1, pp. 13-18.

- This article clearly and concisely explains the complexity that is choosing a UV-blocking window film. Like a scientific paper it discusses how different films were tested for UV transmittance as well as color change. It is possible that the films tested for this study are no longer available or perform differently now that this 2010 article is six years old. It is still a useful resource and introduction to the world of UV films, and would be an ideal place to start for anyone starting to look to purchase films. Unfortunately this article does not consider price, which would be a major consideration for most institutions. It also does not address aging properties, another key characteristic of window films. They highlight some unacceptable films, which is key information to have when considering which to purchase.

Michalski, S. 1997. The lighting decision. *Fabric of an Exhibition, Preprints of Textile Symposium 97*. Ottawa: Canadian Conservation Institute: pp. 97-104.

- This is a key reading about the tension and balance between visibility of objects and light damage. Michalski discusses the need for conservators to broaden their lighting benchmarks for museum and for them to adopt a more complex case-specific outlook. The article contains a useful and simple chart that explains basic steps for museums/historic houses where either total control of lighting is possible or if partial lighting control is possible. The article also explains details about human vision, and how we see differently based on factors like age and the style of lighting. Another table provides lightfastness ratings of natural dyes on wool, cotton, and silk. This would be valuable if one knew the dye components of a textile. While not completely useful to the everyday employee, this article is a valuable source for anyone invested in preventive conservation.

Himmelstein, P., and B. Appelbaum. 2000. An overview of light and lighting in historic structures that house collections. *APT Bulletin.* 31(1): 13-15.

- This article outlines basic ideas for mitigating light in historic houses. It is indeed an overview and only a few pages long, yet lays the foundation for understanding the complexities of collection care in a historic structure. It discusses the tension between visibility and preservation, and the potential for the use of lighting as an interpretive element. The authors primarily focus on fixture lighting but also briefly discuss daylight. While likely too basic for most conservation professionals, this is a good starting place and explains lighting issues well.

Tétreault J., and C. Anuzet. 2015. Ultraviolet Filters - Canadian Conservation Institute (CCI) Notes 2/1. <http://canada.pch.gc.ca/eng/1439925170062>

Other Sources

Sergey, P. 2015. Email communication concerning inventory of Nakashima archives at the James Michener Museum. Archivist and Volunteer Manager, James A. Michener Museum, Doylestown, PA.

Bing, S., J. Herrick, and A. Yates Krain. 2003. Conservation and treatment reports for six Nakashima drawings on paper. The Conservation Center for Art & Historic Artifacts (CCAHA). Philadelphia, PA.

Keeping it Modern: 2015 Grant Awardees. The Getty Foundation. http://www.getty.edu/foundation/initiatives/current/keeping_it_modern/grants_awarded_2015.html

National Historic Landmark Nomination Form: George Nakashima Woodworker Complex.

www.nps.gov/nhl/news/LC/.../Nakashima.pdf

Peirce, L. 2016. Personal communication about data analysis. Winterthur Museum, Gardens, and Library. Winterthur, DE.

Wallis, S. 2015. New carpets honor Nakashima's designs. *Architectural Digest*, April 30, 2015. Published by Condé Nast. <http://www.architecturaldigest.com/story/edward-fields-george-nakashima-carpets-article>

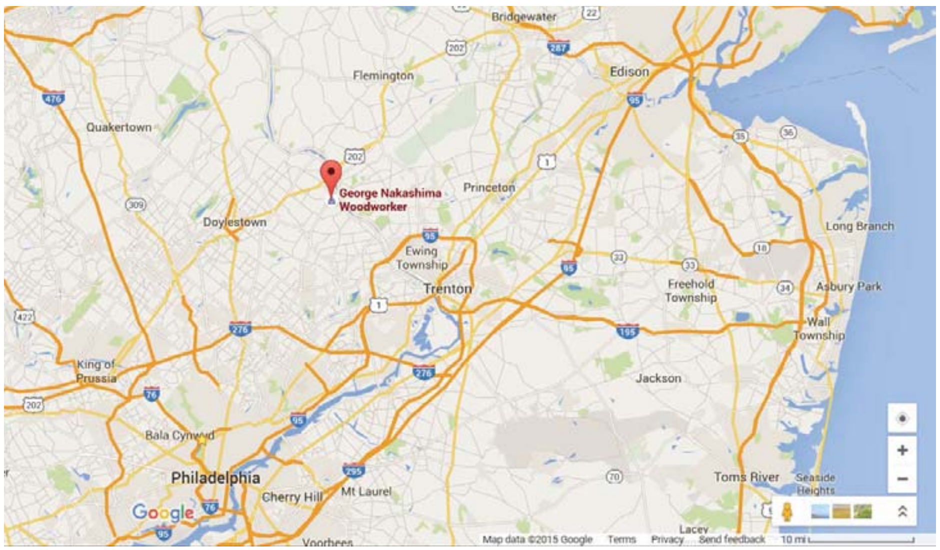
Appendix C

Nakashima Art Studio Daylighting Study.
Shin-Yi Kwan and Janki A. Vyas,
Master of Environmental Building Design (MEBD),
School of Design, University of Pennsylvania, 2016

LOCATION + BACKGROUND

General Background

George Nakashima (1905-1990), the internationally-renowned architect, furniture designer and woodworker, first moved to New Hope, Pennsylvania with his family in 1943. They moved from Idaho where they were interned at Camp Minidoka for two years after the Japanese attacked Pearl Harbor. Shortly after the war ended in 1946, Nakashima bartered three acres of land along Aquatong Road in Solebury Township in exchange for carpentry work. Between 1946 and 1954, the three-acre site consisted of two buildings, the Nakashima House and Workshop. As Nakashima's furniture business gained notoriety, the site grew into twenty-one buildings spread across a 12.2-acre tract, known today as the George Nakashima Woodworker Complex. In 2008, the Nakashima Woodworker Complex was added to the National Register of Historic Places. The instrumental role Nakashima played in constructing nineteen of the complex's buildings led to their "contributing" status. In 2013, the Nakashima Woodworker Complex was designated a **National Historic Landmark**. This proposal is focused on the International-style Arts Building, which was completed in 1967 to exhibit the artwork of Nakashima's friend, Ben Shahn, one of the nineteen contributing buildings.



WEATHER FILE USA_NJ_Trenton-Mercer.County.AP.724095_TMY3

SITE ADDRESS 1847 Aquetong Rd, New Hope, PA 18938

LATITUDE + LONGITUDE 40.339348, -74.954851

The Arts Building

The Arts Building has footprint of roughly 36 by 40 feet and measures 23 feet in height at its tallest point. It is a single story structure with a loft in the southwest corner; oriented to the south to maximize solar gain in the winter, while deciduous trees around the building provide shade in the summer.

The north and east walls are composed of concrete masonry units (CMU) parged with a cementitious stucco on the exterior. The CMU walls are insulated with Styrofoam boards adhered to the interior face, covered with lath, and finished with Structolite plaster. The south and west walls consist primarily of fixed, custom-sized, single- and double-pane glazing set in site-fabricated cypress wood framing. Protruding from and receding into the southwest corner of the main space is a cast-in-place, reinforced concrete bay one-story in height with a slab roof used as an exterior porch and interior mezzanine.

The south wall is pierced at grade by two door openings. The western-most opening is in the poured concrete bay that enters into the vestibule; the opening is filled with a site-made, wood panel door. The second opening consists of a glazed, sliding-double door located at the center of the south wall that enters directly into the main gallery space. The glazed west wall is penetrated at grade by the sliding sashes of the one-story-tall tripartite window. The operable glazing from mezzanine consists of sliding door in the south wall providing access to the porch and stacked, three-light casement windows at the corner peak of the south and west walls.

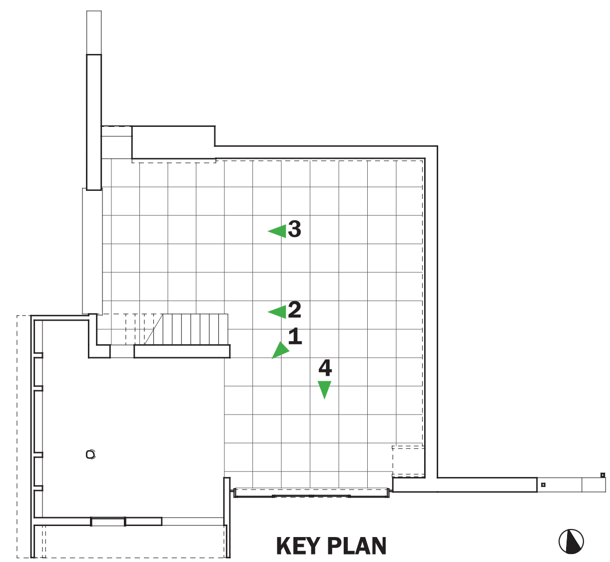
The hyperbolic paraboloid roof, which is the buildings most distinguishing feature, covers the main gallery space of the Arts Building. The roof is constructed of three layers of 5/8" plywood that extends over the CMU and glazed walls creating an eave of approximately 2 feet. The inside face of the roof is left exposed with the long seams between plywood sheets running east to west and concealed with wooden ribs. For strength, the middle layer of plywood was laid perpendicular to the bottom and top layers with the long seam running north to south.

1 MAIN SPACE SOUTHWEST CORNER

2 MAIN SPACE WEST @ STAIR

3 MAIN SPACE WEST

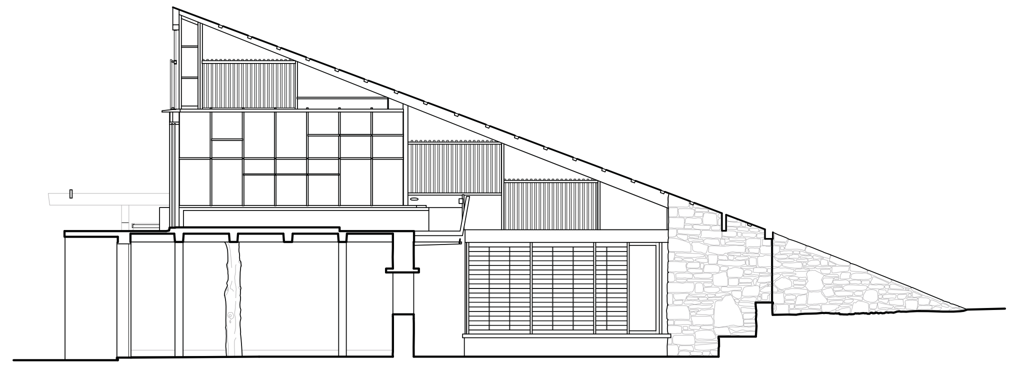
4 MAIN SPACE SOUTH



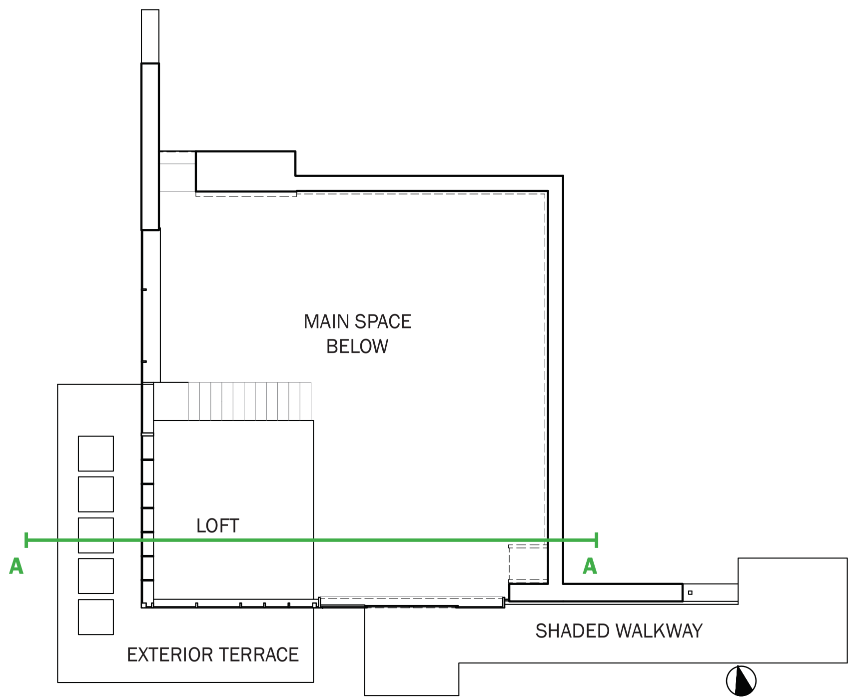
KEY PLAN

ARCHITECTURE

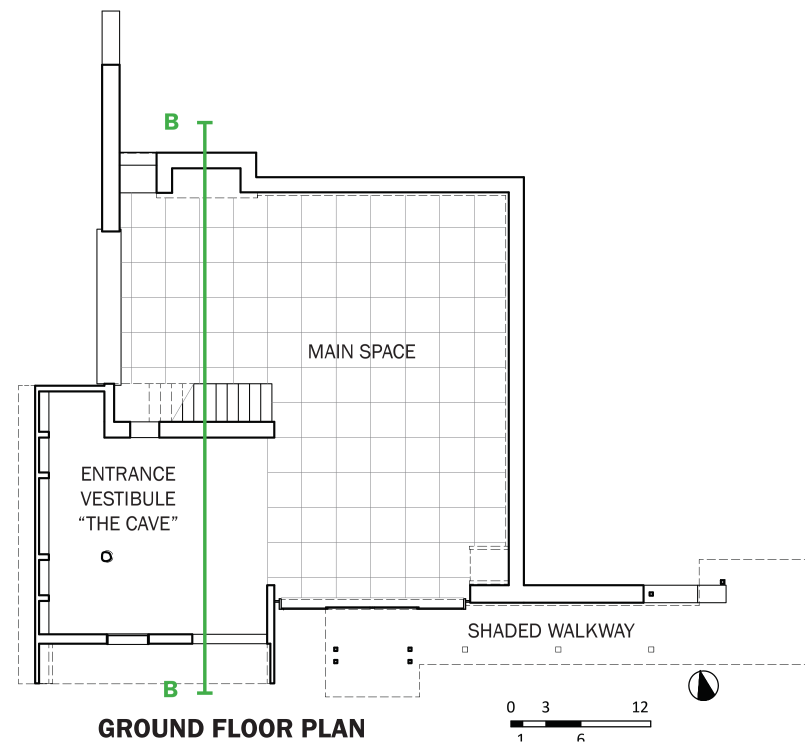
SECTION A-A



SECTION B-B



LOFT PLAN



GROUND FLOOR PLAN

METRICS FOR DAYLIGHTING MUSEUM BUILDINGS AND OBJECTS

TABLE 3.1
Recommended Total Exposure Limits in Terms of Illuminance Hours Per Year to Limit Light Damage to Susceptible Museum and Art Gallery Artifacts

Note: All ultraviolet radiation (400 nm and below) should be eliminated.

Types of Materials	Maximum Illuminance (Neither value should be exceeded)	Lux-Hours/Yr
Highly susceptible displayed materials: textiles, cotton, natural fibers, furs, silk, writing inks, paper documents, lace, fugitive dyes, watercolors, wool, some minerals.	50 lux	50,000
	Note: Approximately (50 lux) × (8 hours per day) × (125 days per year). Different levels (higher or lower) and/or different periods of display (4 hours for 250 days) may be appropriate, depending upon material. If in doubt, consult a conservator.	
Moderately susceptible displayed materials: textiles with stable dyes, oil paintings, wood finishes, leather, some plastics.	200 lux	480,000
	Note: Approximately (200 lux) × (8 hours per day) × (300 days per year). Lower levels may be appropriate, depending upon material. If in doubt, consult a conservator.	
Least susceptible displayed materials: metal, stone, glass, ceramic, most minerals.	Dependent upon exhibition situation.	

IESNA Museum and Art Gallery Lighting: A Recommended Practice, p.14.

METRICS FOR DAYLIGHTING NON-MUSEUM BUILDINGS AND PEOPLE

Daylight Autonomy (DA) & Useful Daylight Illumination (UDI)

A measure of the percentage of occupied hours a point in a space receives a required illuminance threshold. This metric does not establish a range of lighting levels, only tells you how often one illuminance value is met. Thus, it is not a good measure of overlit spaces. To account for overlit spaces a variation of DA, Useful Daylight Illuminance, which establishes three thresholds, how often the illuminance on a point is below 100 lux, between 100 and 2,500 and over 2,500. UDI considers values above 2,500 lux to be in the glare or thermal discomfort.

Spatial Daylight Autonomy (sDA)

A measure of how much of a space receives sufficient daylight. Results of an sDA simulation identify the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

Annual Sun Exposure (ASE)

A measure of how much of a space receives too much direct sunlight, which can cause visual discomfort (glare) or increase cooling loads. ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year.*

Both ASE and sDA are typically used together because sDA has no upper limit on illuminance levels, allowing spaces with too much direct sunlight to appear as well performing. By assigning a higher threshold, ASE provides the balance and indicates areas with potential lighting problems.

** For the purposes of this assignment, the occupancy schedule is adjusted to reflect annual daylit hours, since objects displayed in the building have a 24/7 occupancy.*

CAVE MATERIALITY + OBJECT INVENTORY

LEATHER SUITCASE (25-100 LUX)

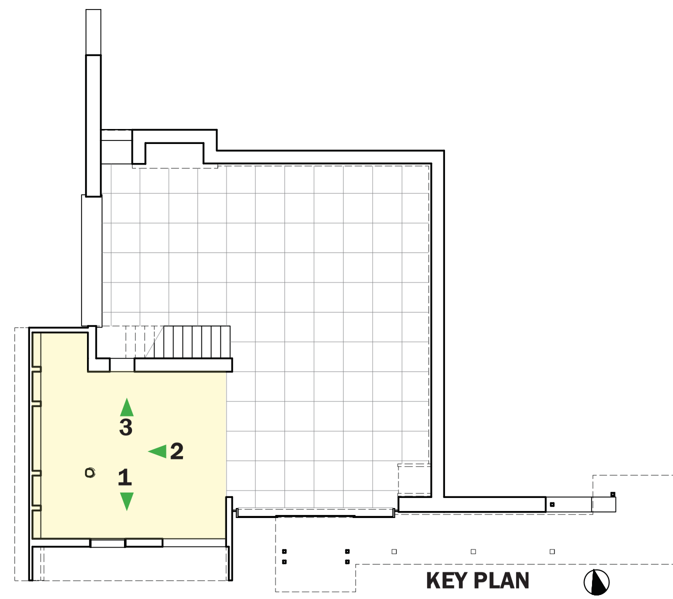
CERAMIC BOWL (500-2000 LUX)

1 "THE CAVE" SOUTH

2 "THE CAVE" WEST

3 "THE CAVE" NORTH

MATERIALS



OBJECT INVENTORY IN SPACE	
RECOMMENDED LIGHT LEVELS	**QTY OF OBJECTS MEETING CRITERIA**
25-100 LUX	21
100-400 LUX	2
500-2000 LUX	1

MAIN SPACE MATERIALITY + OBJECT INVENTORY

WOOD LUTE (25-100 LUX)

METAL HELMET (500-2000 LUX)

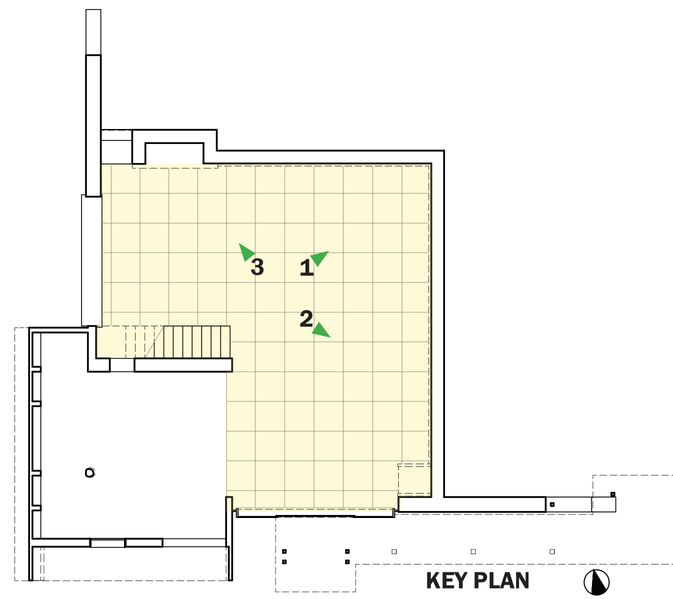
OBJECT INVENTORY IN SPACE	
RECOMMENDED LIGHT LEVELS	**QTY OF OBJECTS MEETING CRITERIA**
25-100 LUX	7
100-400 LUX	5
500-2000 LUX	13

1 MAIN SPACE NORTHEAST CORNER

2 MAIN SPACE EAST

3 MAIN SPACE NORTHWEST CORNER

MATERIALS



KEY PLAN

LOFT MATERIALITY + OBJECT INVENTORY

WOOD CRAVINGS (100-400 LUX)

PAPER DOLLS (25-100 LUX)

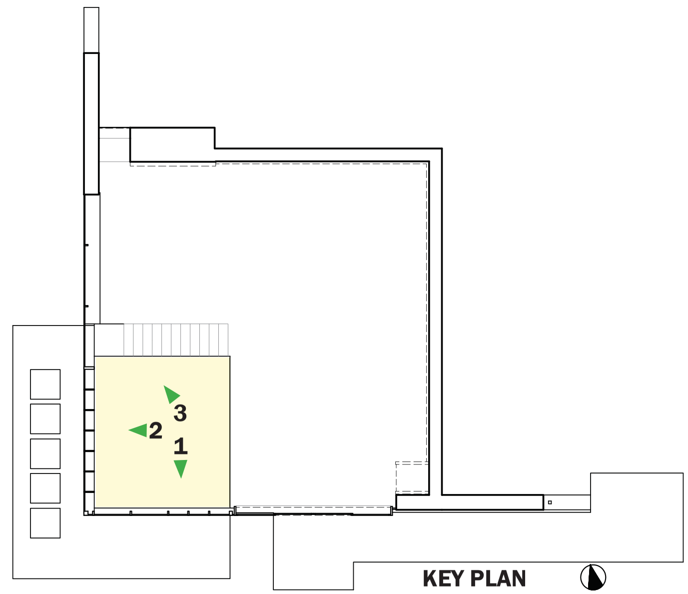
OBJECT INVENTORY IN SPACE	
RECOMMENDED LIGHT LEVELS	**QTY OF OBJECTS MEETING CRITERIA**
25-100 LUX	11
100-400 LUX	8
500-2000 LUX	21

1 LOFT WEST

2 LOFT SOUTH

3 LOFT NORTHWEST CORNER

MATERIALS



KEY PLAN

SIMULATION MODEL INPUTS + SETUP

DAYLIGHT SIMULATION PARAMETERS

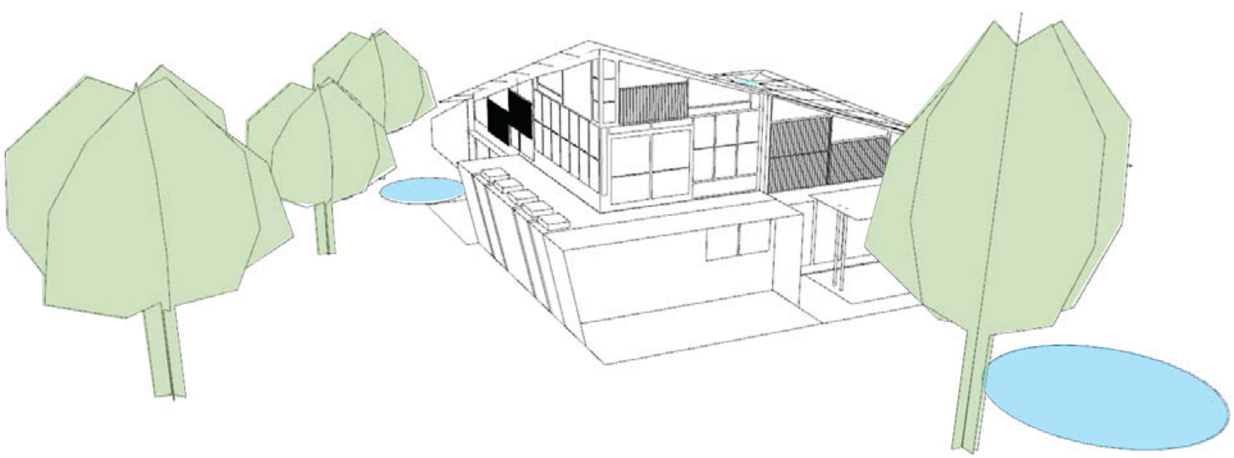
SIMULATION TOOL: DIVA

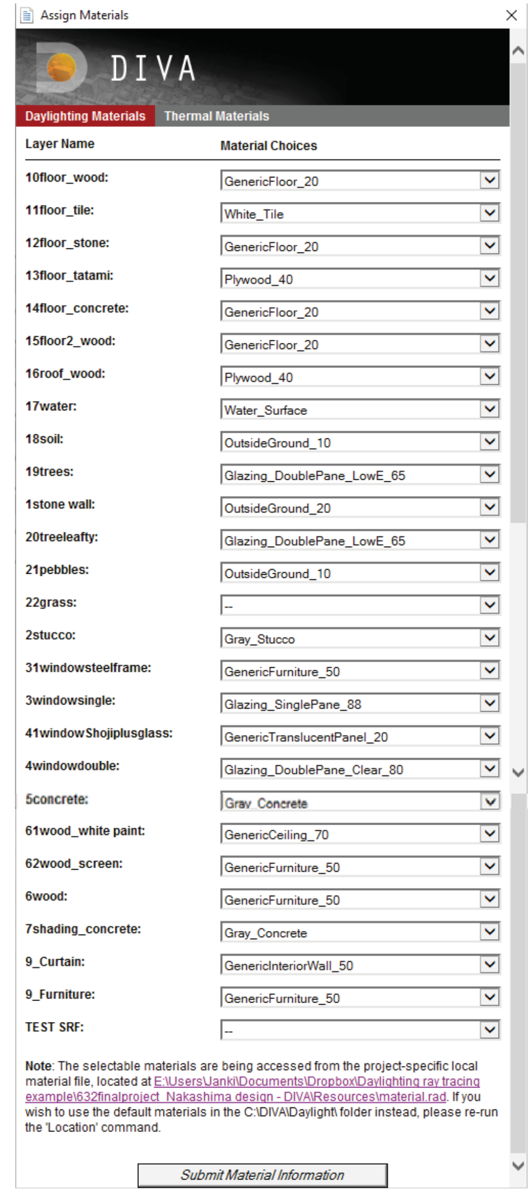
SIMULATION GRID: FLOOR: 2'-6" AFF @ 1'-6" ON CENTER
WALLS: 0'-1" OFF WALL @ 1'-6" ON CENTER

POINT- IN-TIME ILLUMINANCE: CLEAR SKY WITH SUN (CIE CLEAR)

RADIANCE PARAMETERS
- Ambient Bounces 3
- Ambient Divisions 1000
- Ambient Sampling 20
- Ambient Resolution 300
- Ambient Accuracy 0.1

CLIMATE BASED DA / SDA : SAME RADIANCE PARAMETERS AS ABOVE + ASSUME OCCUPANT CAN ADJUST FOR GLARE





Assign Materials

DIVA

Daylighting Materials | Thermal Materials

Layer Name	Material Choices
10floor_wood:	GenericFloor_20
11floor_tile:	White_Tile
12floor_stone:	GenericFloor_20
13floor_tatami:	Plywood_40
14floor_concrete:	GenericFloor_20
15floor2_wood:	GenericFloor_20
16roof_wood:	Plywood_40
17water:	Water_Surface
18soil:	OutsideGround_10
19trees:	Glazing_DoublePane_LowE_65
1stone wall:	OutsideGround_20
20treeleafty:	Glazing_DoublePane_LowE_65
21pebbles:	OutsideGround_10
22grass:	--
2stucco:	Gray_Stucco
31windowsteelframe:	GenericFurniture_50
3windowsingle:	Glazing_SinglePane_88
41windowShojiplusglass:	GenericTranslucentPanel_20
4windowdouble:	Glazing_DoublePane_Clear_80
5concrete:	Gray_Concrete
61wood_white paint:	GenericCeiling_70
62wood_screen:	GenericFurniture_50
6wood:	GenericFurniture_50
7shading_concrete:	Gray_Concrete
9_Curtain:	GenericInteriorWall_50
9_Furniture:	GenericFurniture_50
TEST SRF:	--

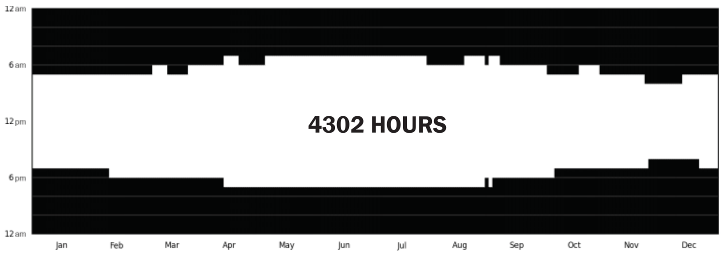
Note: The selectable materials are being accessed from the project-specific local material file, located at E:\Users\Janki\Documents\Dropbox\Daylighting ray tracing example\632finalproject_Nakashima design - DIVA\Resources\material.rad. If you wish to use the default materials in the C:\DIVA\Daylight\ folder instead, please re-run the 'Location' command.

Submit Material Information

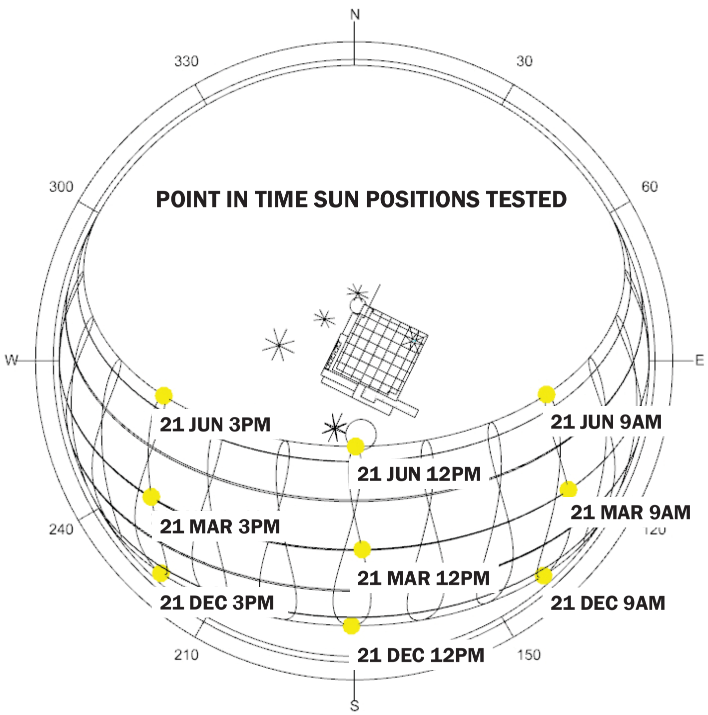
NAKASHIMA ART STUDIO

SIMULATION MODEL INPUTS + SETUP

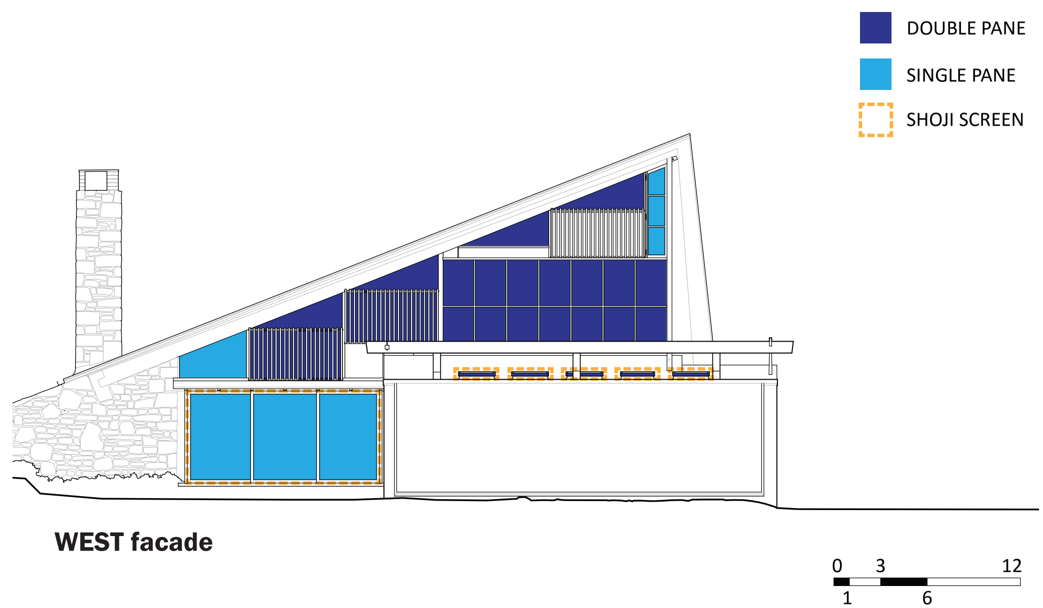
MODIFIED OCCUPIED HOURS SCHEDULE CORRESPONDING WITH DAYLIGHT HOURS [DOES NOT CONSIDER DAYLIGHT SAVINGS]



POINT IN TIME SUN POSITIONS TESTED



SOUTH facade

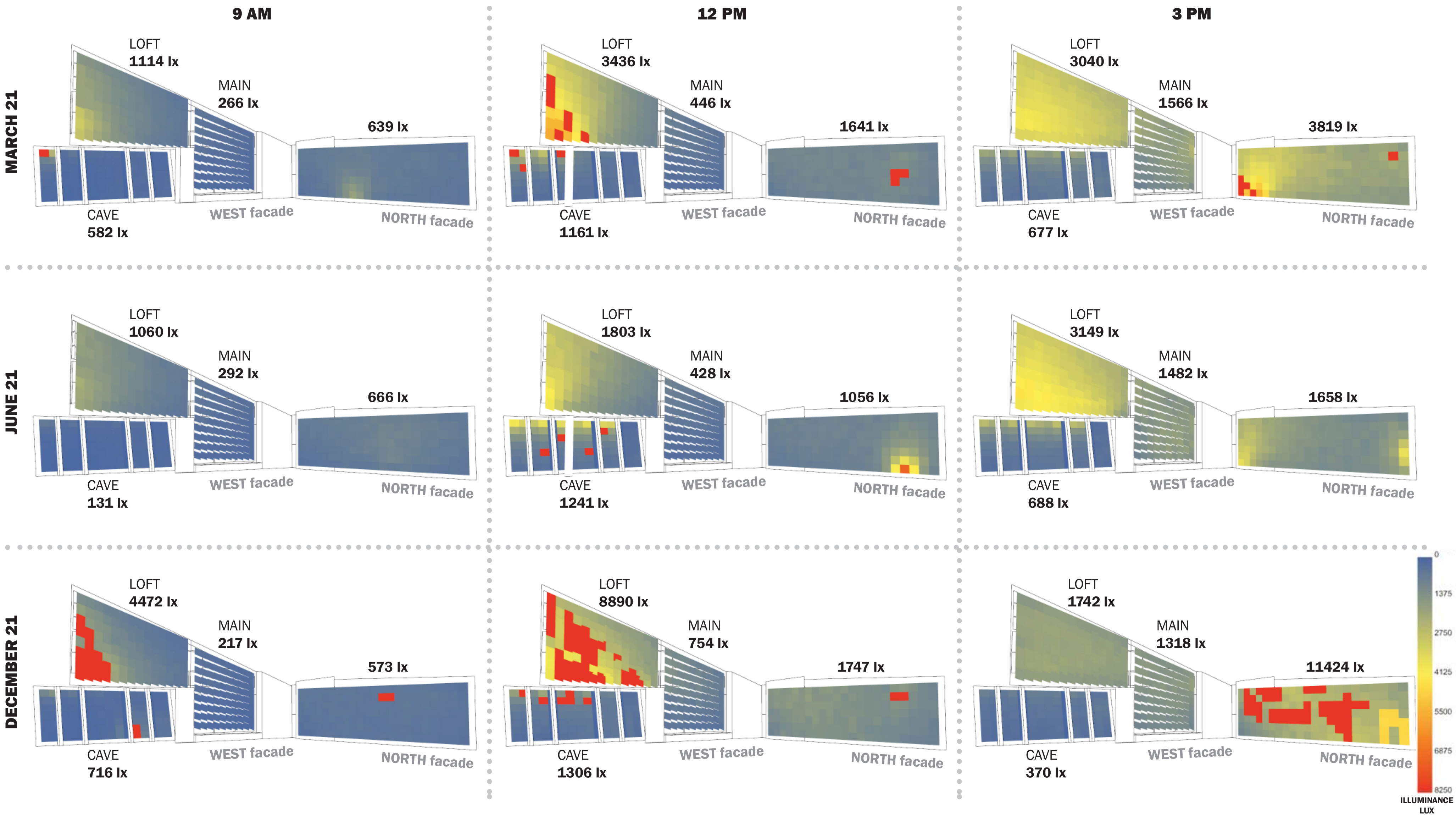


WEST facade

NAKASHIMA ART STUDIO

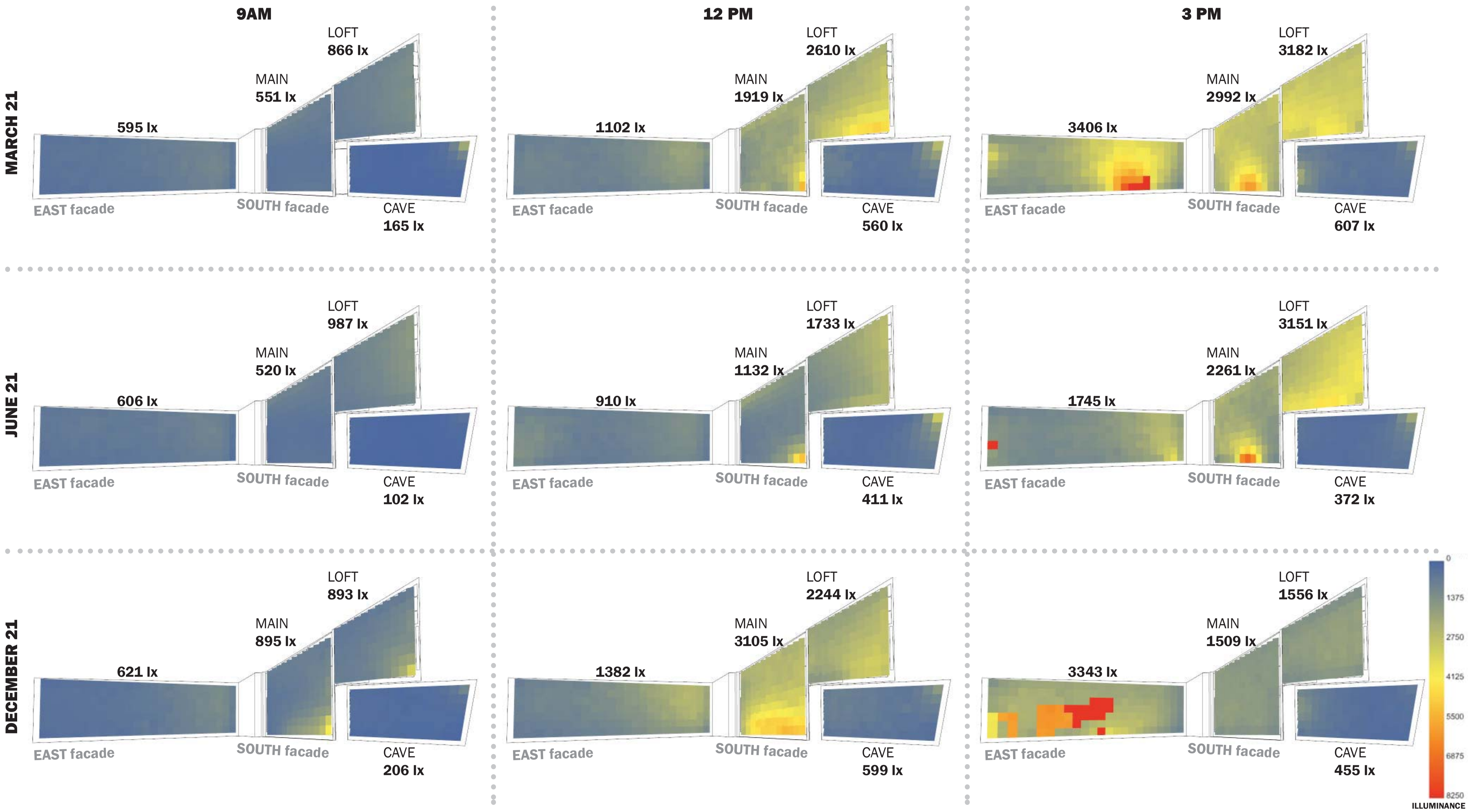
baseline_DAYLIGHTING FOR OBJECTS_north + west facade

Mean illumance lux values listed for point-in-time simulations

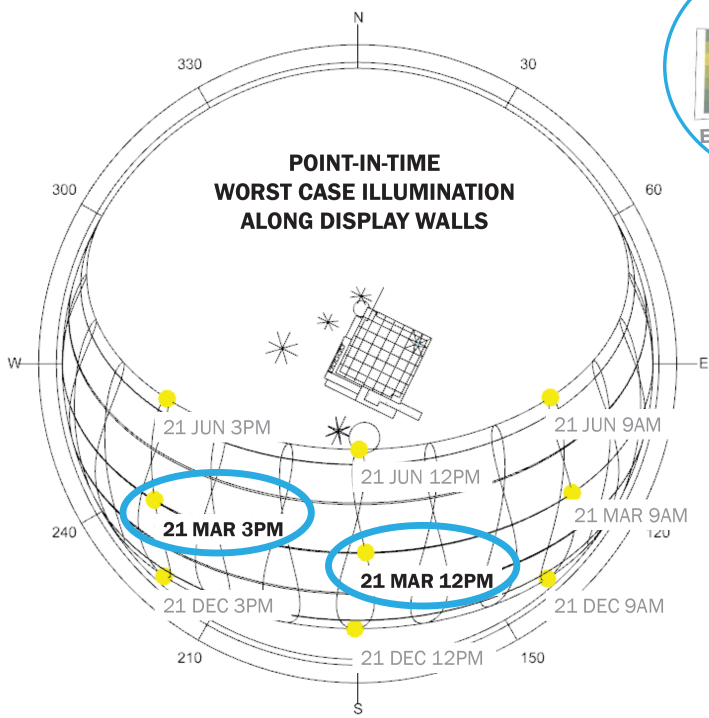


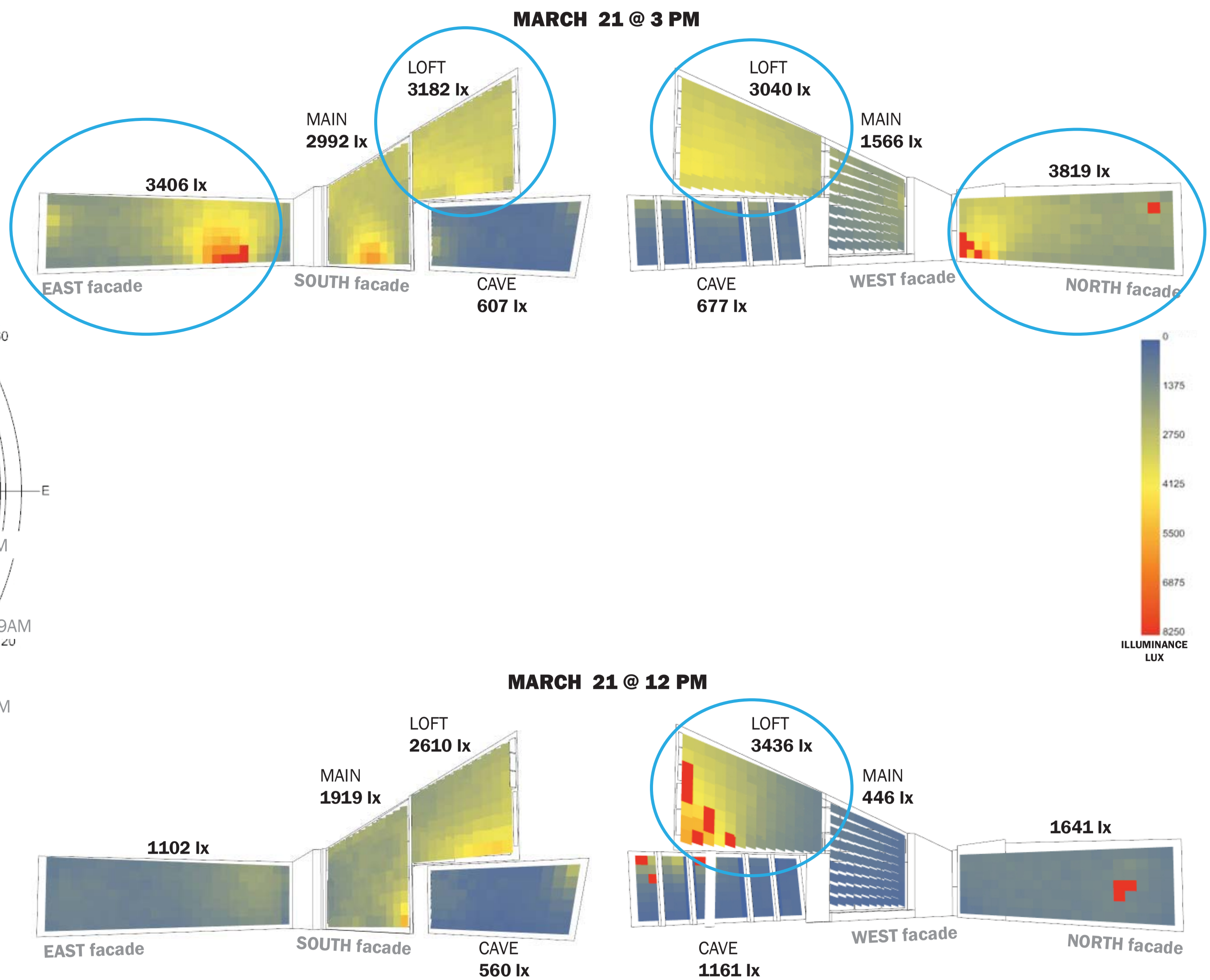
baseline_DAYLIGHTING FOR OBJECTS_south + east facade

Mean illumance lux values listed for point-in-time simulations

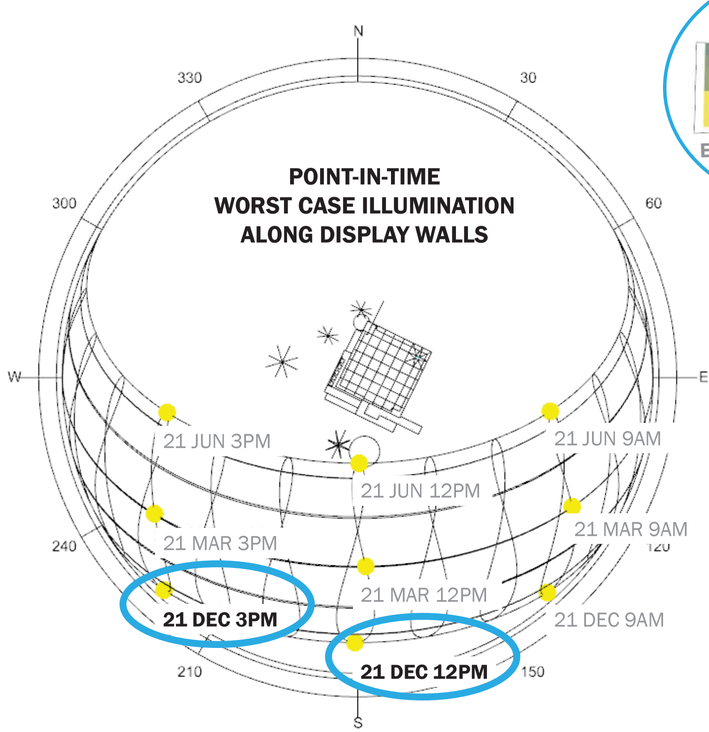


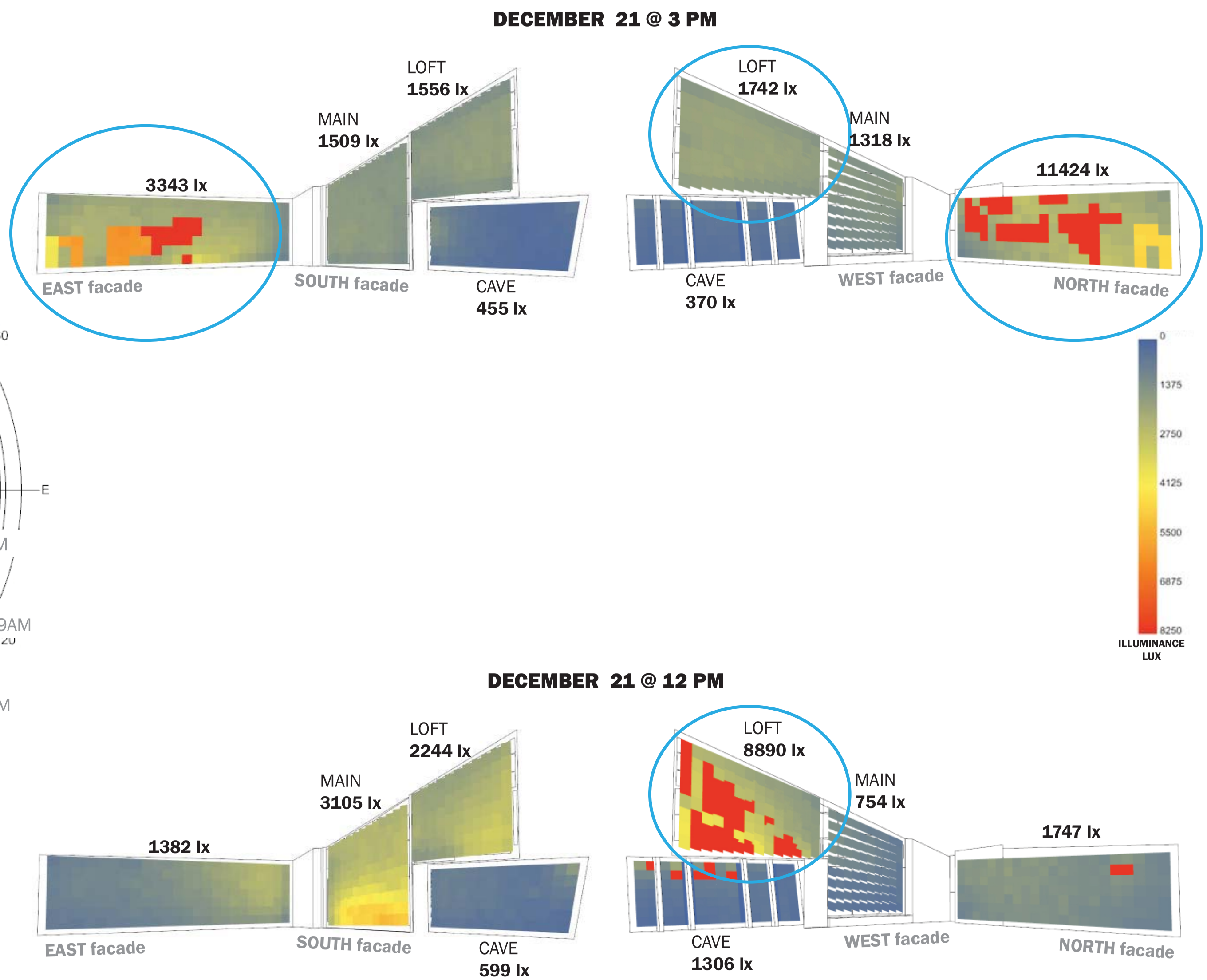
analysis_WORST CASE CONDITION_point-in-time identification





analysis_WORST CASE CONDITION_point-in-time identification

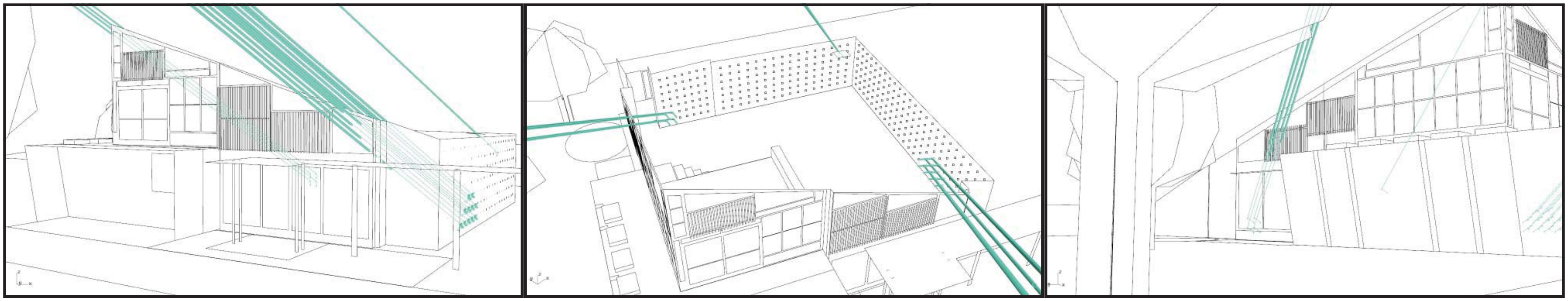




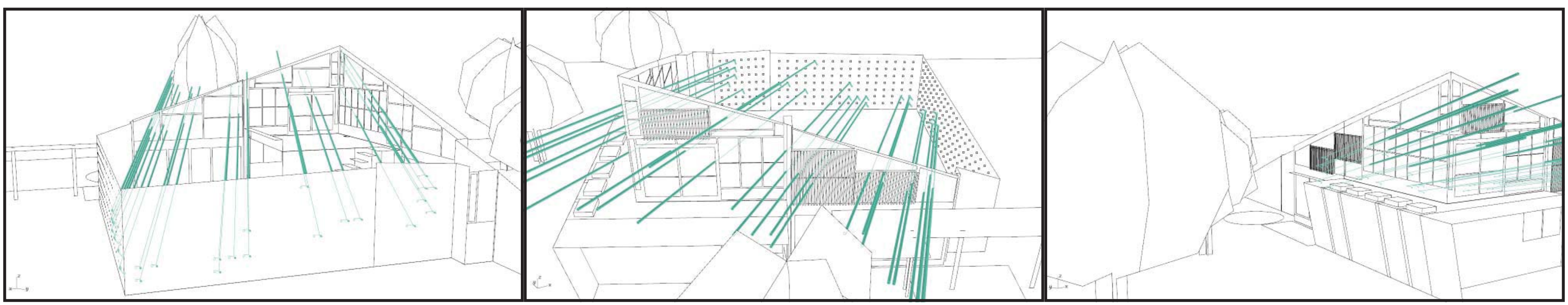
analysis_WORST CASE CONDITION_raytracing

Raytracing the suns path allows us to see which windows are contributing to the harshest direct solar radiation levels, so that we may devise a plan to minimize the amount of direct solar gain.

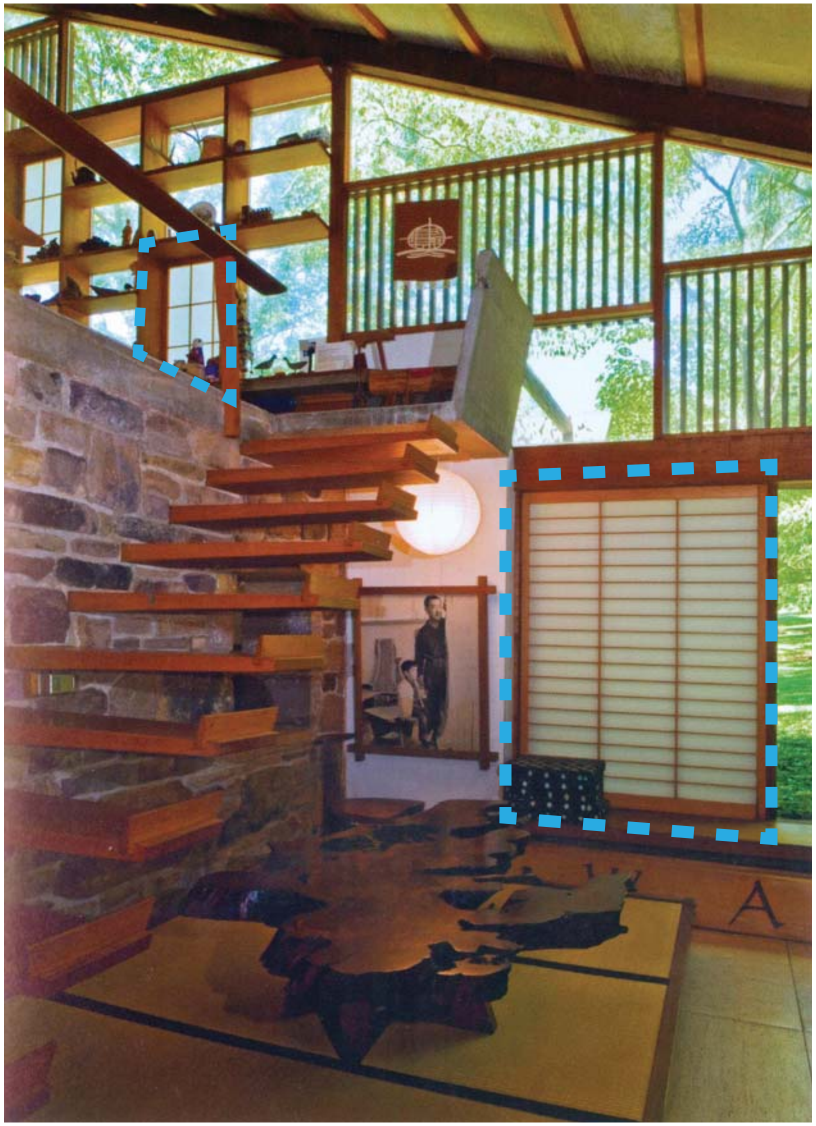
MARCH 21 @ 3 PM



DECEMBER 21 @ 3 PM



analysis_HISTORIC CONDITION_minimal intervention approach



In conjunction with the raytracing exercise we researched the buildings history to determine what, if any, changes occured to the buildings original design. This helped us to take field observation and historical research into account when determining what minimial interventions we can pursue to minimize direct solar gain. There were three main findings:

1. At the south facade there are curtains that the client can pull closed during harsh sun light hours.

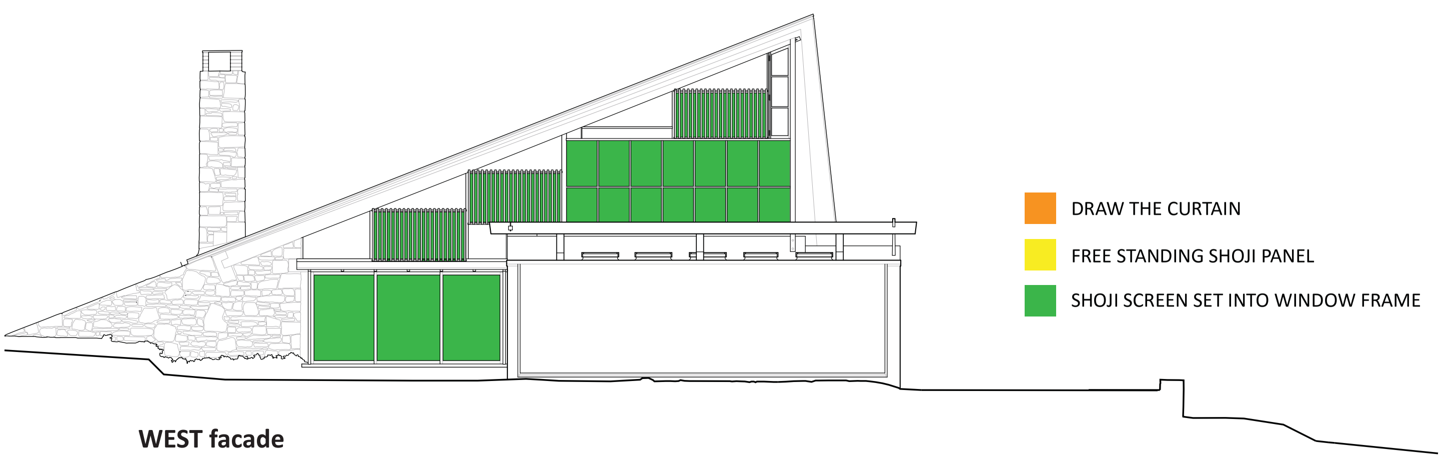
2. There is a free standing shoji screen in the loft that can be relocated over the course of the day based on where the sun is.

3. There used to be shoji panels built-in the loft display shelving along the west facade.

Our design proposal looks at the effects of pulling shades, locating the freestanding shoji panel and reinstalling the built-in shoji panels along the west facade. In addition, our raytracing found that light was making it's way into the building from the exterior slatted wood screening, so we proposed additional shoji panels to be installed interior of the glazing at the screen.

proposed_INTERVENTION PLAN

SOUTH facade



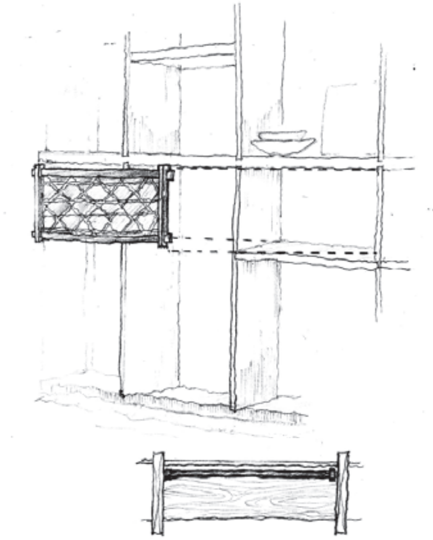
WEST facade

DRAW THE CURTAIN

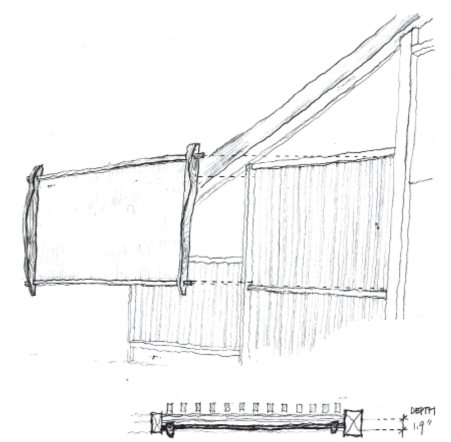
FREE STANDING SHOJI PANEL

SHOJI SCREEN SET INTO WINDOW FRAME

0 3 12
1 6

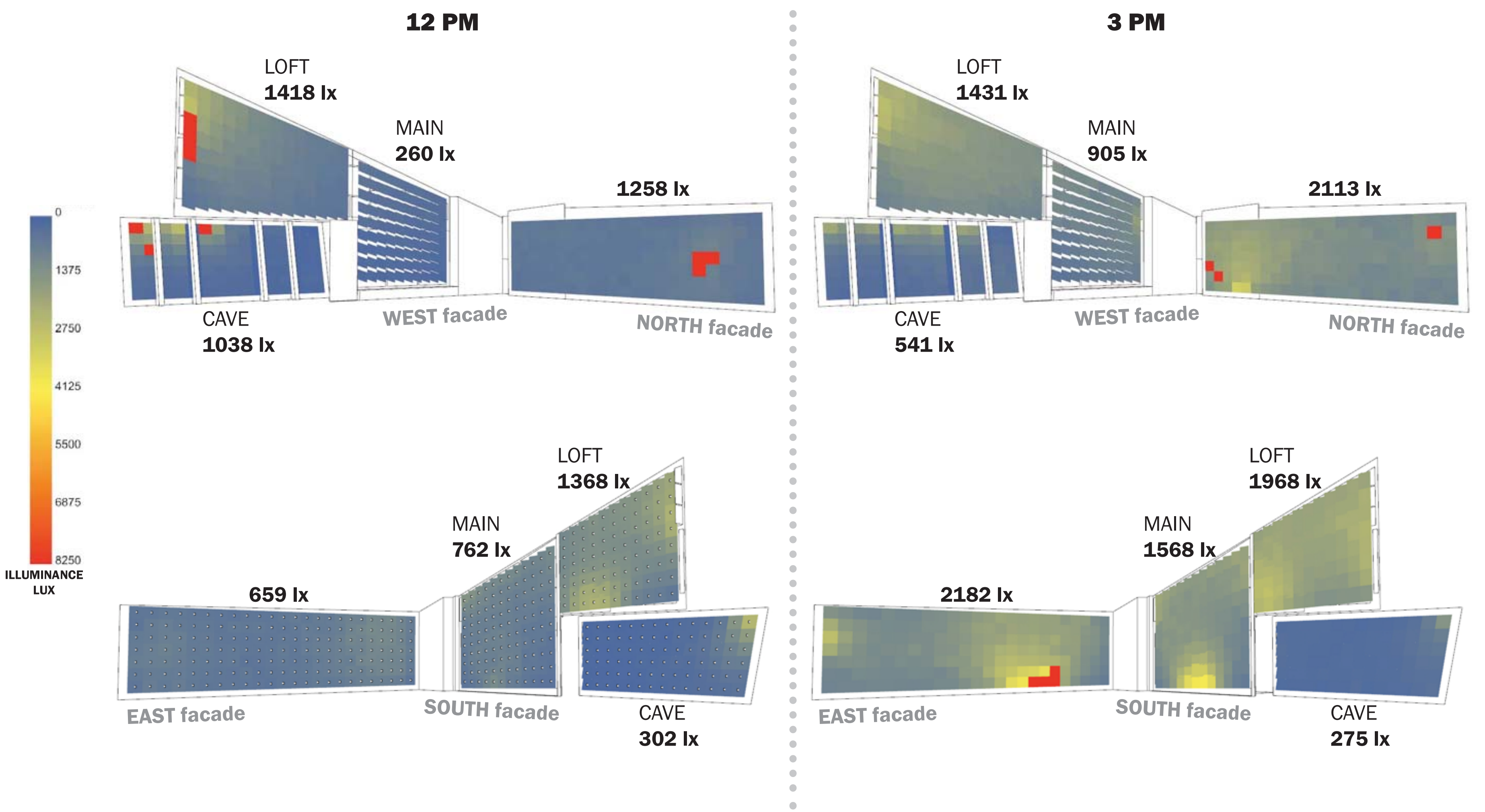


SHOJI SCREEN SET @ LOFT SHELVING

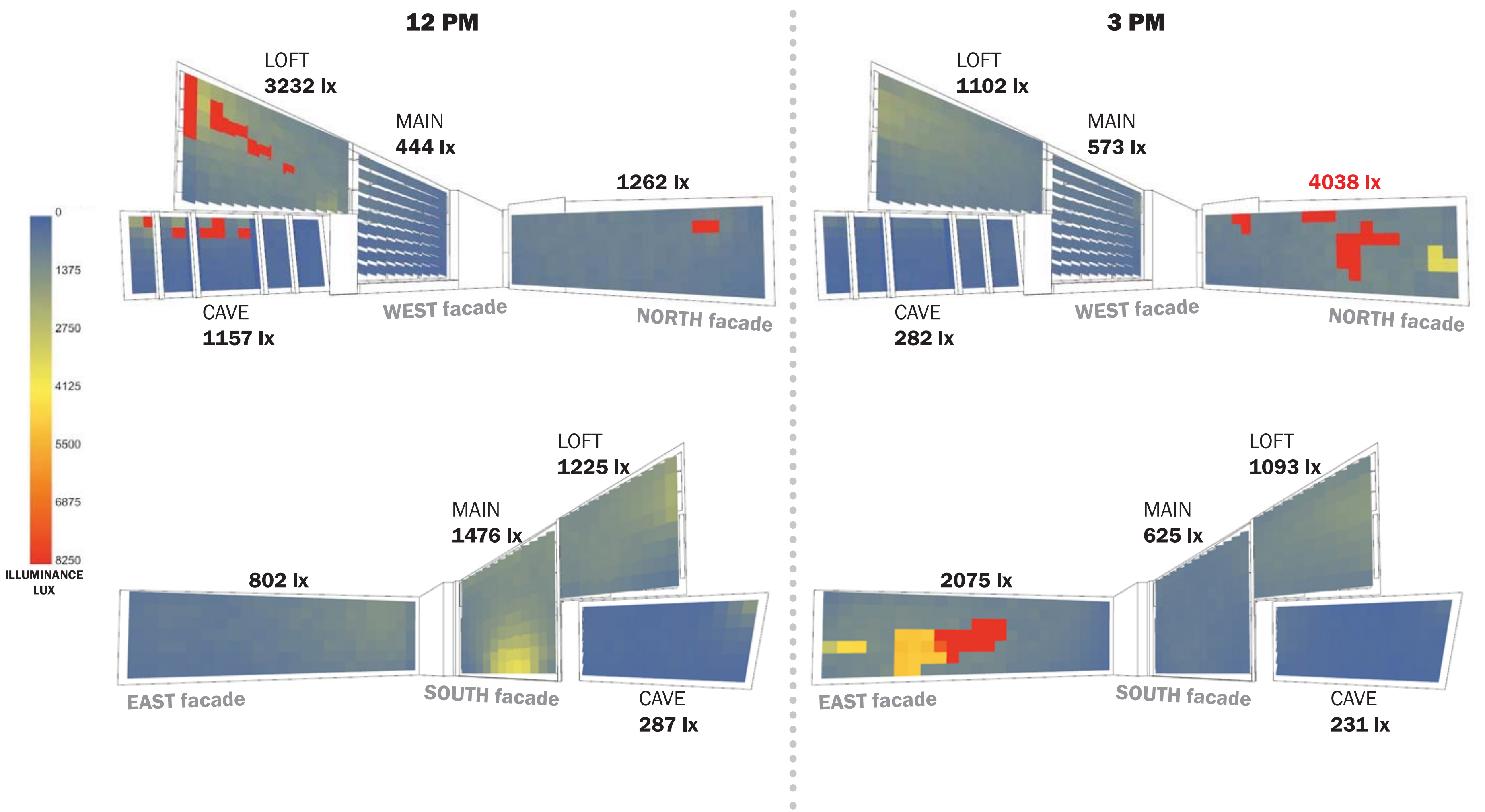


SHOJI SCREEN SET @ EXTERIOR SLATTED WOOD SCREENS

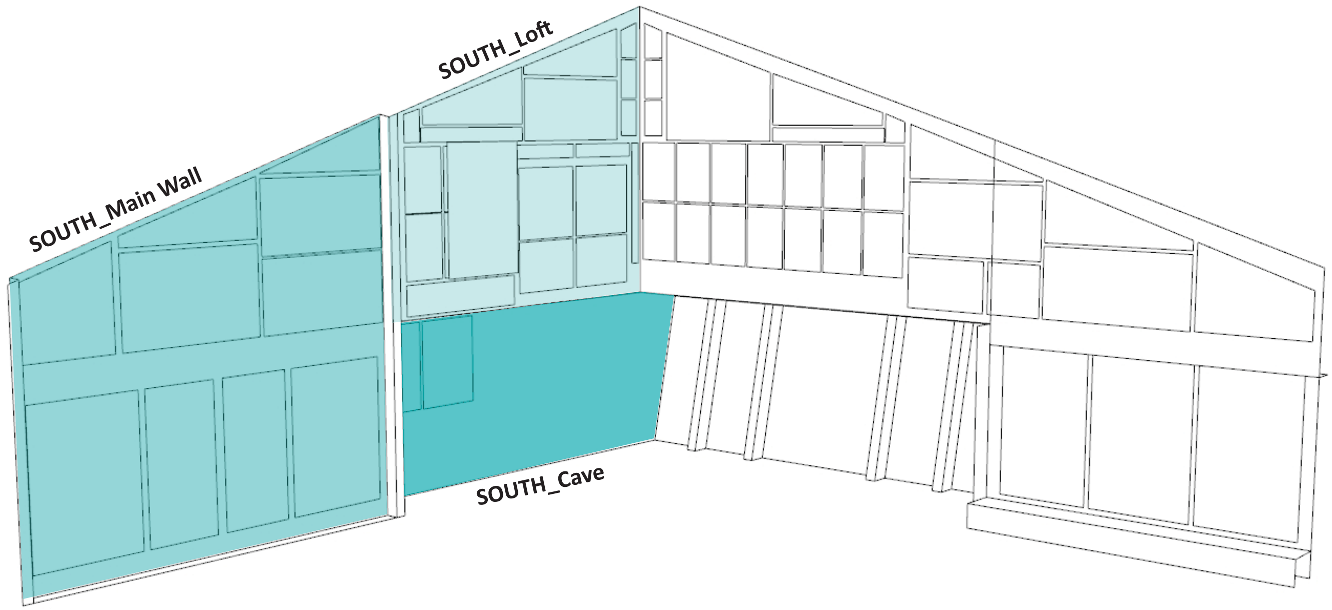
proposed_DAYLIGHTING FOR OBJECTS_march 21

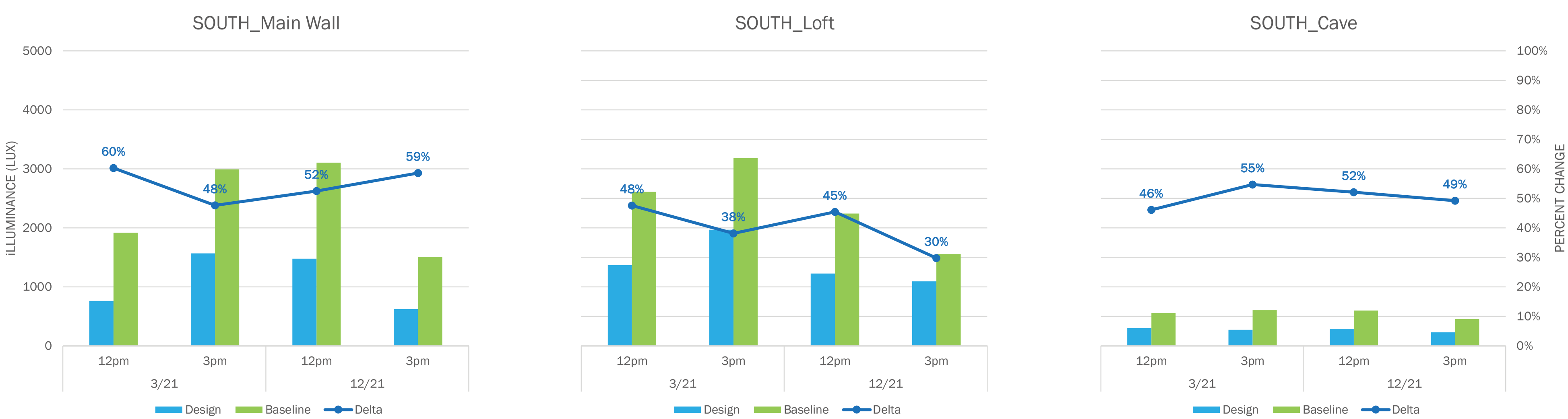


proposed_DAYLIGHTING FOR OBJECTS_december 21



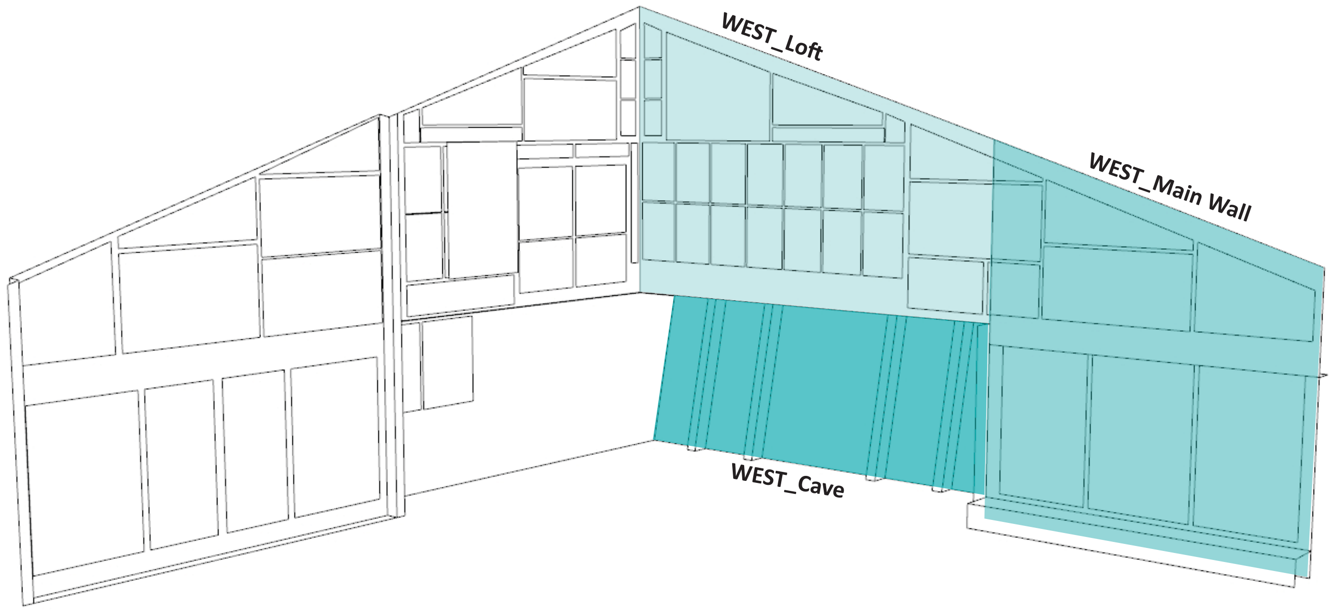
baseline + proposed_COMPARISON

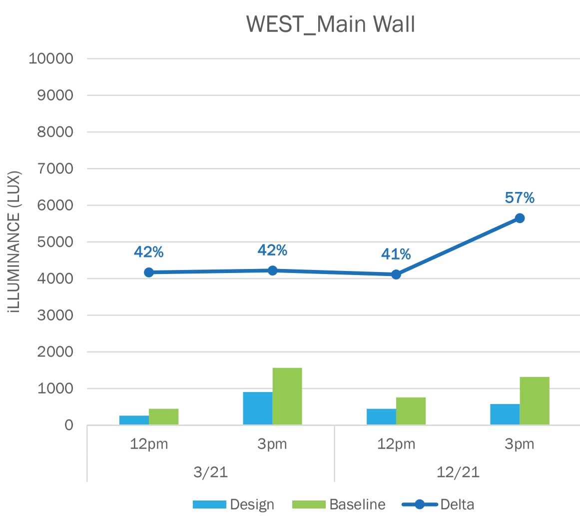


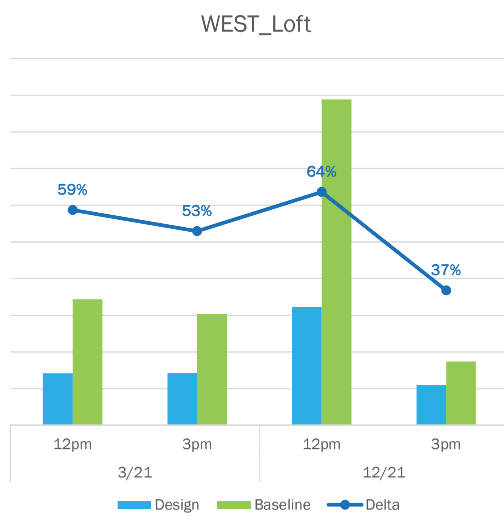


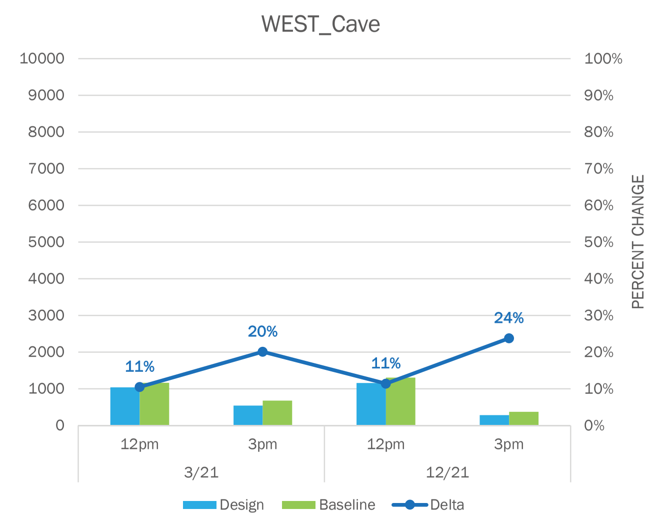
NAKASHIMA ART STUDIO

baseline + proposed_COMPARISON

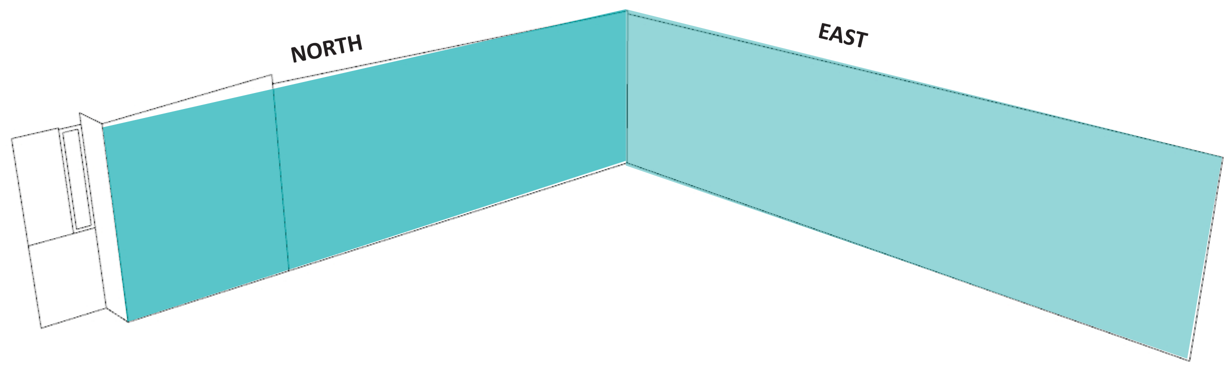


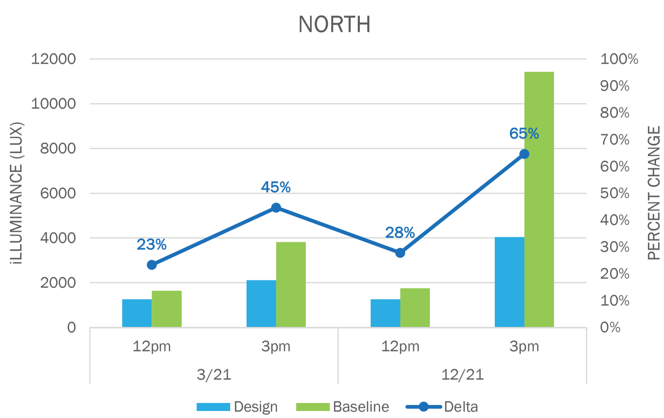


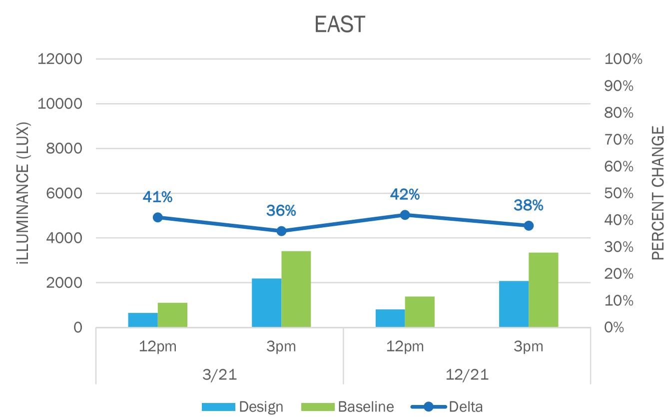




baseline + proposed_COMPARISON

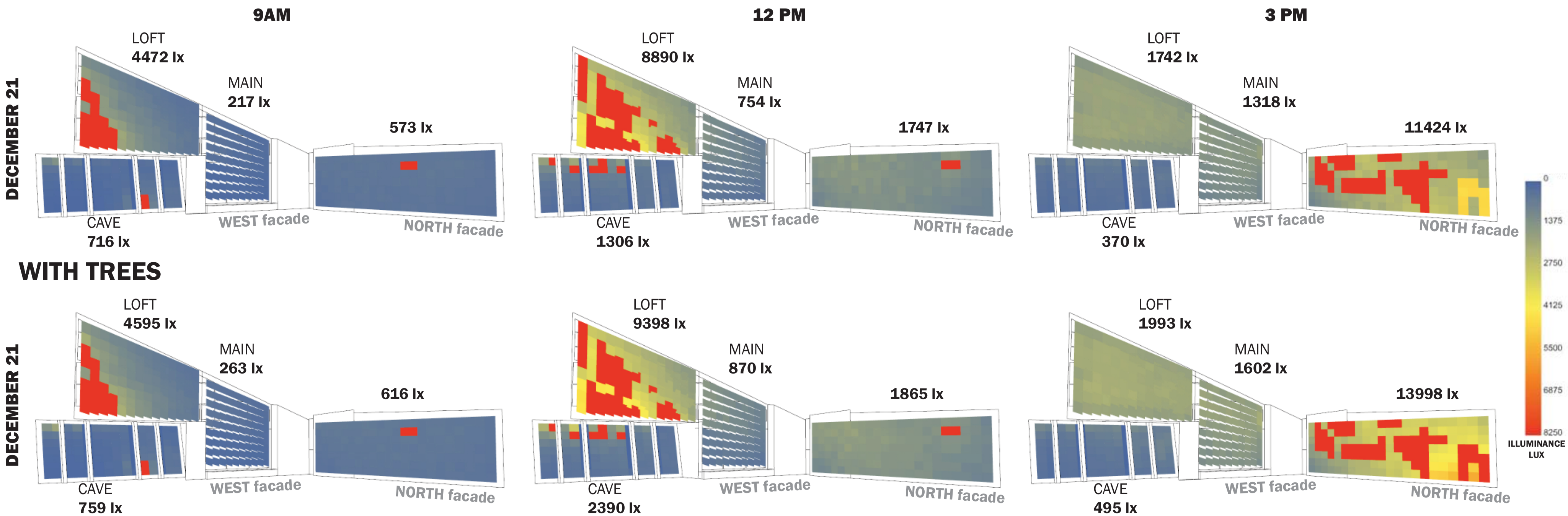


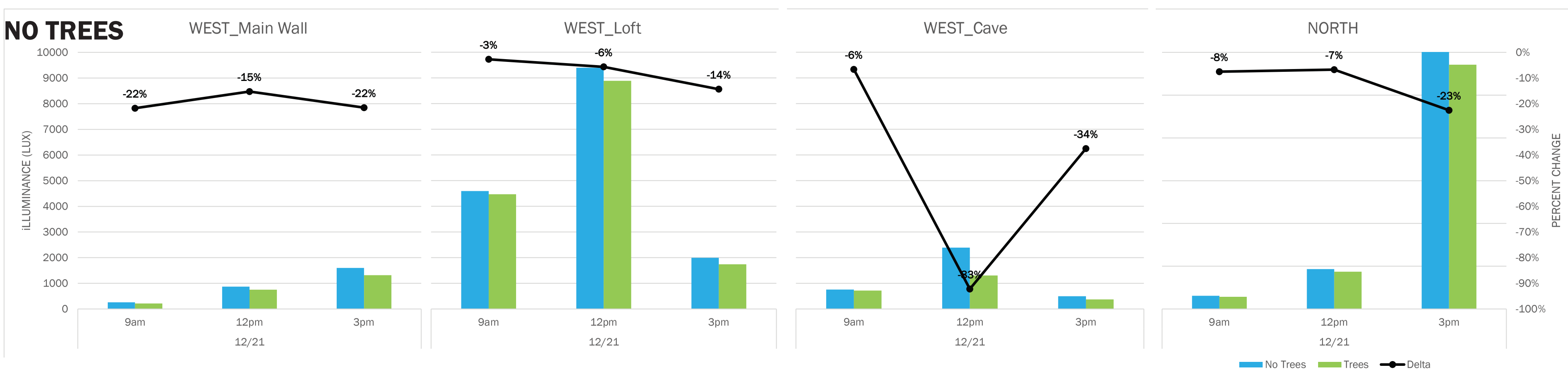




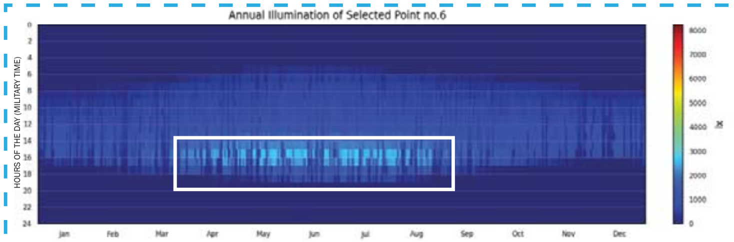
NAKASHIMA ART STUDIO

Effect of Vegetation

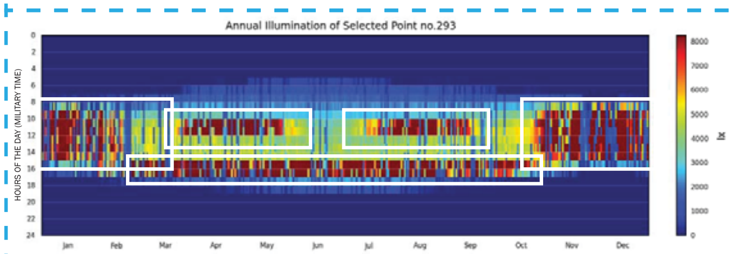




baseline_DAYLIGHTING FOR OCCUPANTS_main space



ANNUAL DAYLIGHT ILLUMINANCE @ 1 POINT NEAR WEST DOORS

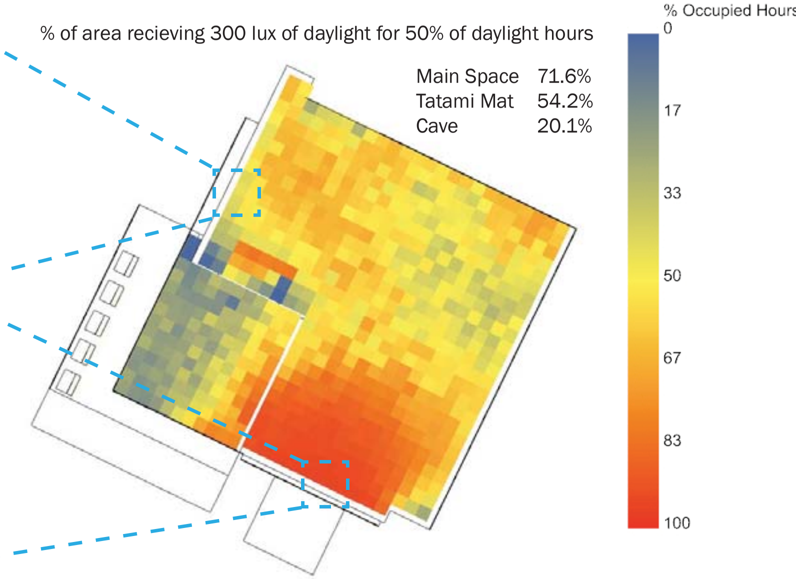


ANNUAL DAYLIGHT ILLUMINANCE @ 1 POINT NEAR SOUTH DOORS

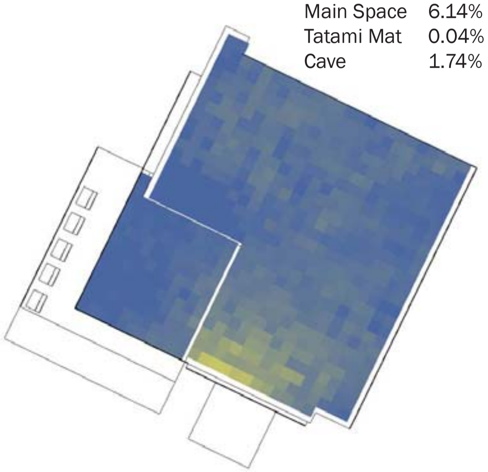
SPATIAL DAYLIGHT AUTONOMY

% of area recieving 300 lux of daylight for 50% of daylight hours

Main Space	71.6%
Tatami Mat	54.2%
Cave	20.1%

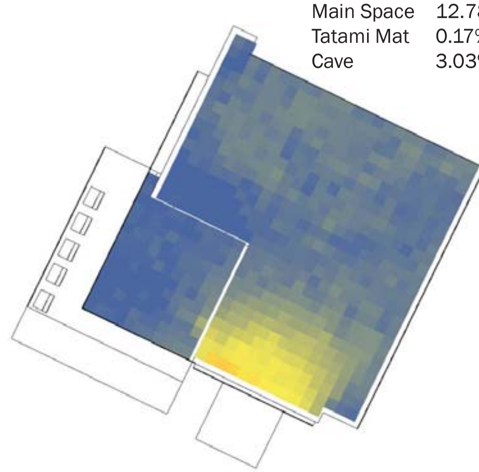


Main Space	6.14%
Tatami Mat	0.04%
Cave	1.74%



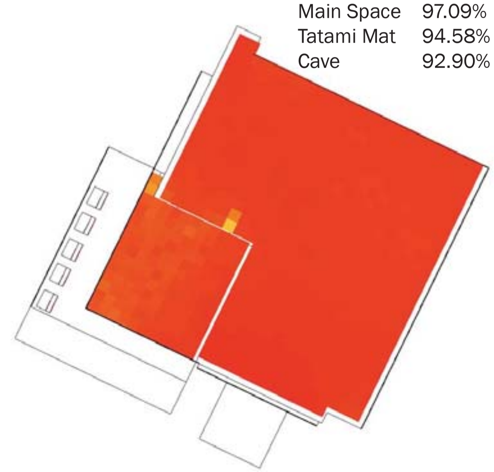
DAYLIGHT AUTONOMY (5,000 LX)

Main Space	12.78%
Tatami Mat	0.17%
Cave	3.03%



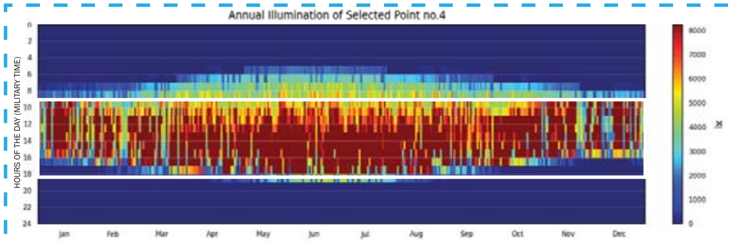
DAYLIGHT AUTONOMY (2,500 LX)

Main Space	97.09%
Tatami Mat	94.58%
Cave	92.90%

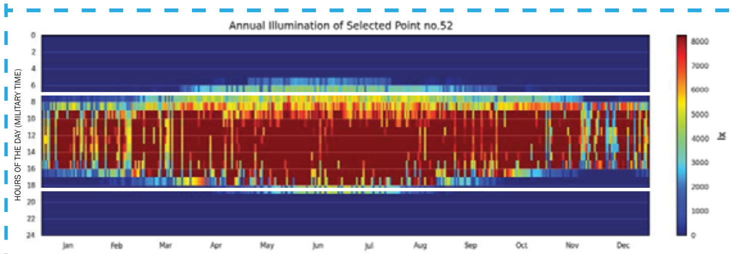


DAYLIGHT AUTONOMY (50 LX)

baseline_DAYLIGHTING FOR OCCUPANTS_loft



ANNUAL DAYLIGHT ILLUMINANCE @ 1 POINT NEAR WEST DOORS

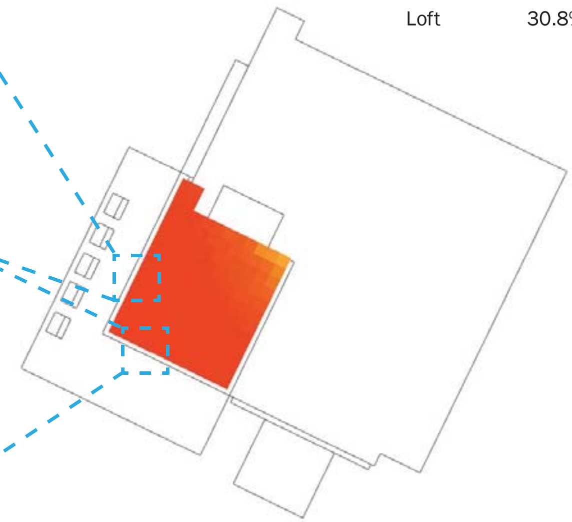


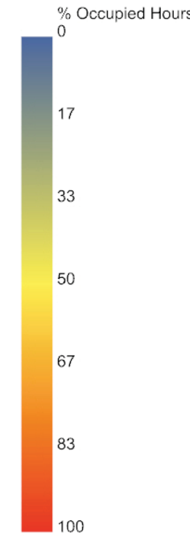
ANNUAL DAYLIGHT ILLUMINANCE @ 1 POINT NEAR SOUTH DOORS

SPATIAL DAYLIGHT AUTONOMY

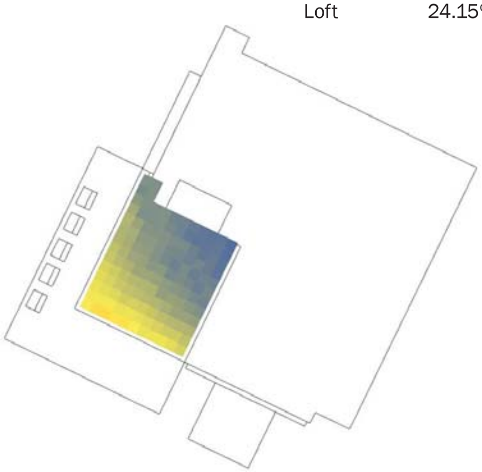
% of area recieving 300 lux of daylight for 50% of daylight hours

Loft 30.8%



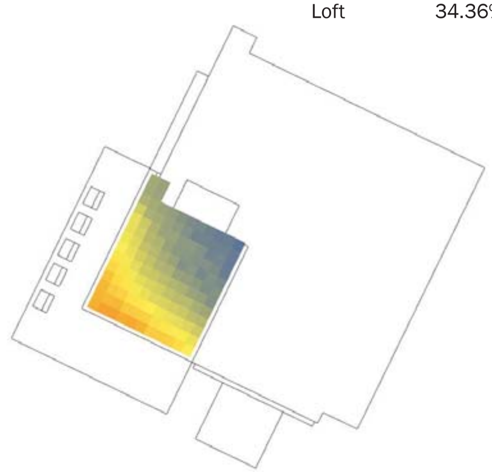


Loft 24.15%



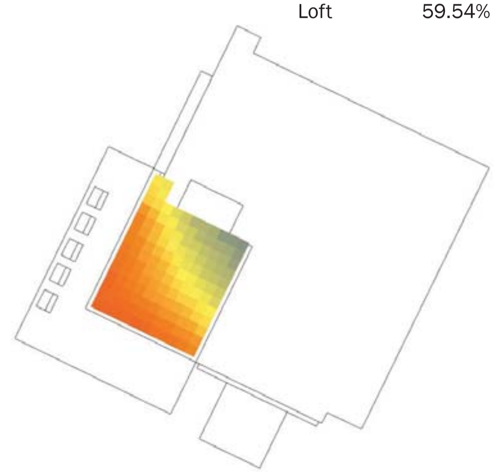
DAYLIGHT AUTONOMY (7,500 LX)

Loft 34.36%



DAYLIGHT AUTONOMY (5,000 LX)

Loft 59.54%



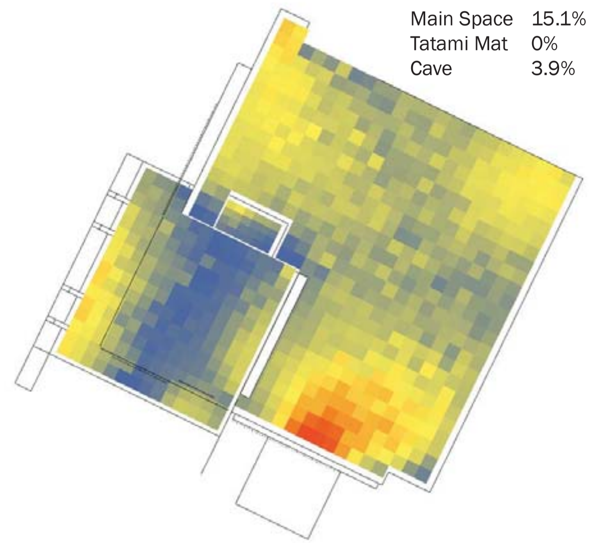
DAYLIGHT AUTONOMY (2,500 LX)

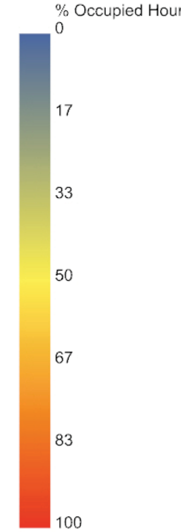
design_DAYLIGHTING FOR OCCUPANTS_main space

SPATIAL DAYLIGHT AUTONOMY

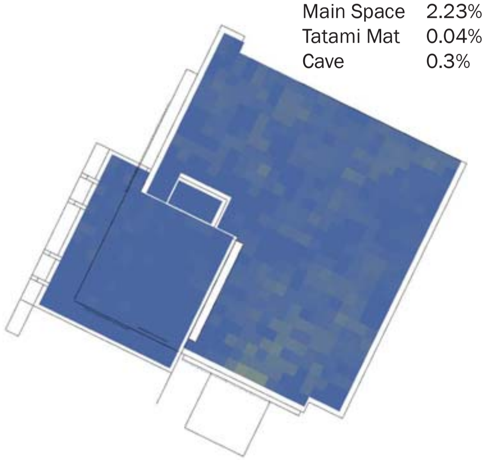
% of area recieving 300 lux of daylight for 50% of daylight hours

Main Space	15.1%	**79% Reduction**
Tatami Mat	0%	**100% Reduction**
Cave	3.9%	**81% Reduction**



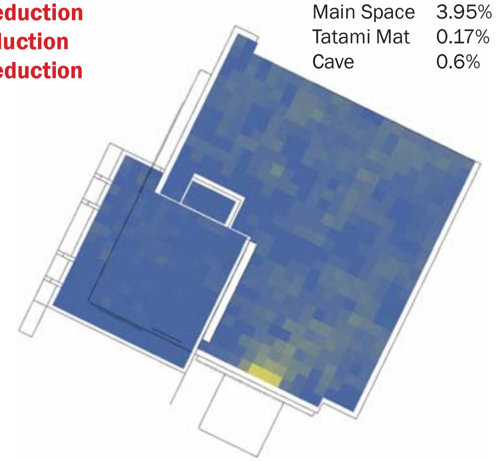


Main Space	2.23%	**64% Reduction**
Tatami Mat	0.04%	**0% Reduction**
Cave	0.3%	**83% Reduction**



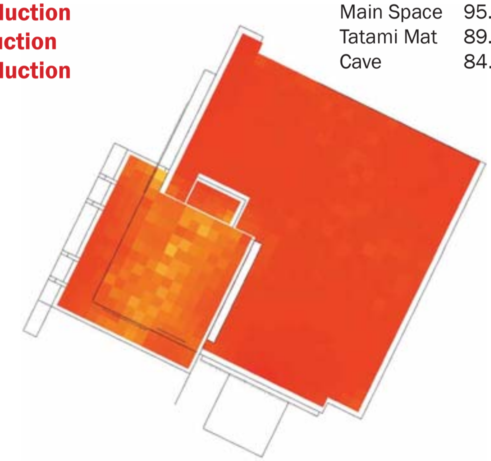
DAYLIGHT AUTONOMY (5,000 LX)

Main Space	3.95%	**69% Reduction**
Tatami Mat	0.17%	**0% Reduction**
Cave	0.6%	**80% Reduction**



DAYLIGHT AUTONOMY (2,500 LX)

Main Space	95.01%	**2% Reduction**
Tatami Mat	89.50%	**5% Reduction**
Cave	84.78%	**9% Reduction**



DAYLIGHT AUTONOMY (50 LX)

design_DAYLIGHTING FOR OCCUPANTS_loft

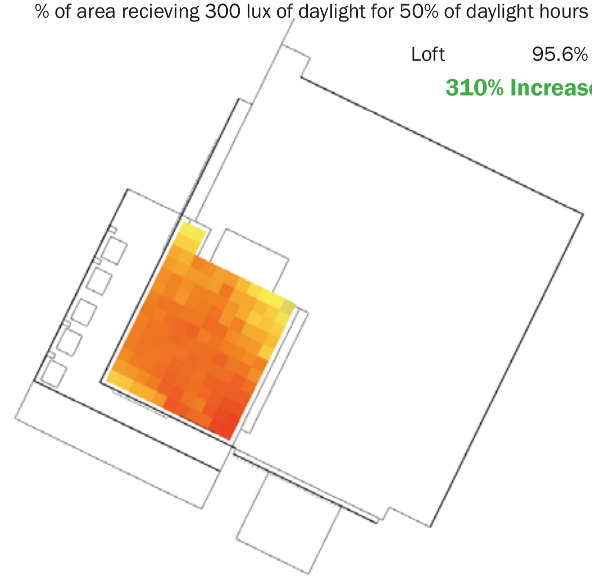
Since these design case simulations show the extreme case condition where all shades are drawn and all panels are employed, it is possible that actual conditions are quite different. However, based on the extreme case, natural lighting levels in the loft area are greatly improved, at the expense of lighting levels in the main space and cave which may require artificial lighting.

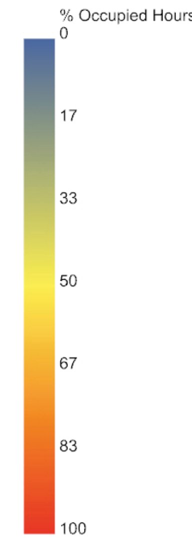
SPATIAL DAYLIGHT AUTONOMY

% of area recieving 300 lux of daylight for 50% of daylight hours

Loft 95.6%

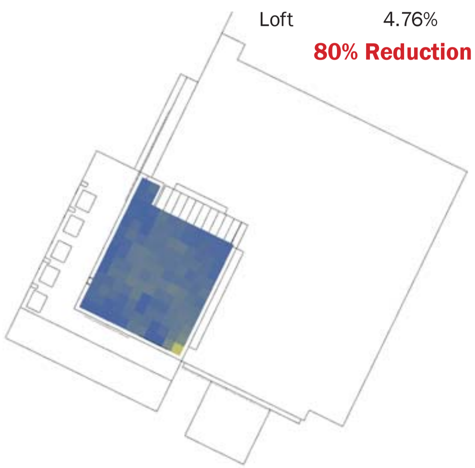
310% Increase





Loft 4.76%

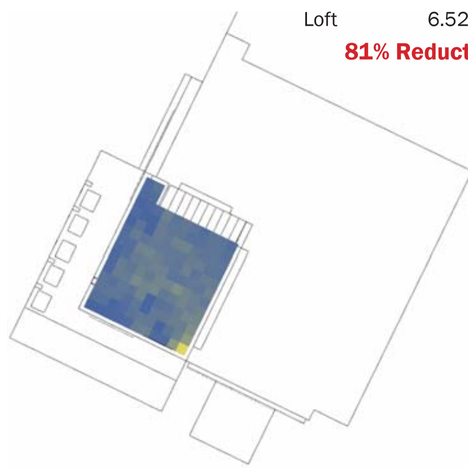
80% Reduction



DAYLIGHT AUTONOMY (7,500 LX)

Loft 6.52%

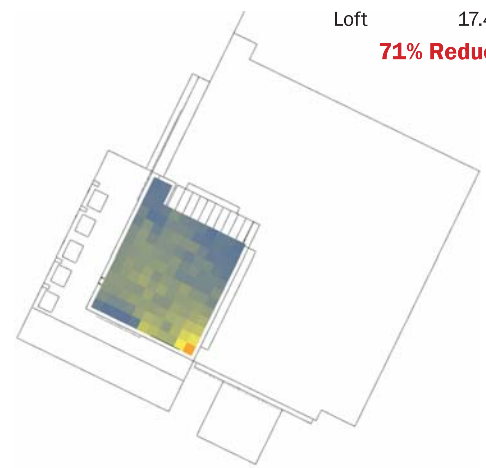
81% Reduction



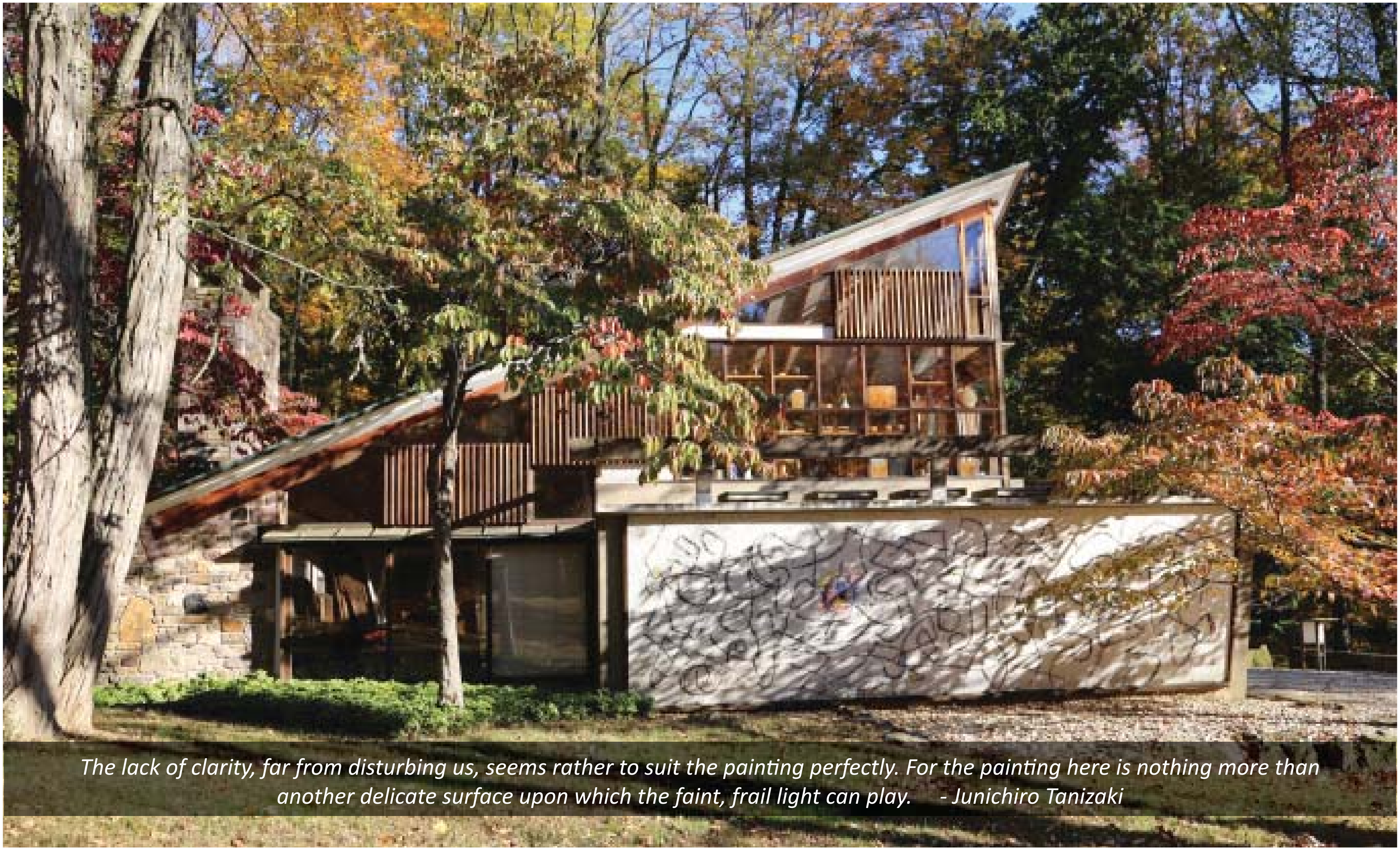
DAYLIGHT AUTONOMY (5,000 LX)

Loft 17.49%

71% Reduction



DAYLIGHT AUTONOMY (2,500 LX)



The lack of clarity, far from disturbing us, seems rather to suit the painting perfectly. For the painting here is nothing more than another delicate surface upon which the faint, frail light can play. *- Junichiro Tanizaki*

Appendix D

Weahter Data for Trenton/Mercer County Airport

TRENTON/MERCER NJ	
Latitude = 40.28 N	WMO No. 724095
Longitude = 74.82 W	Elevation = 213 feet
Period of Record = 1973 to 1996	Average Pressure = 29.77 inches Hg

Design Criteria Data

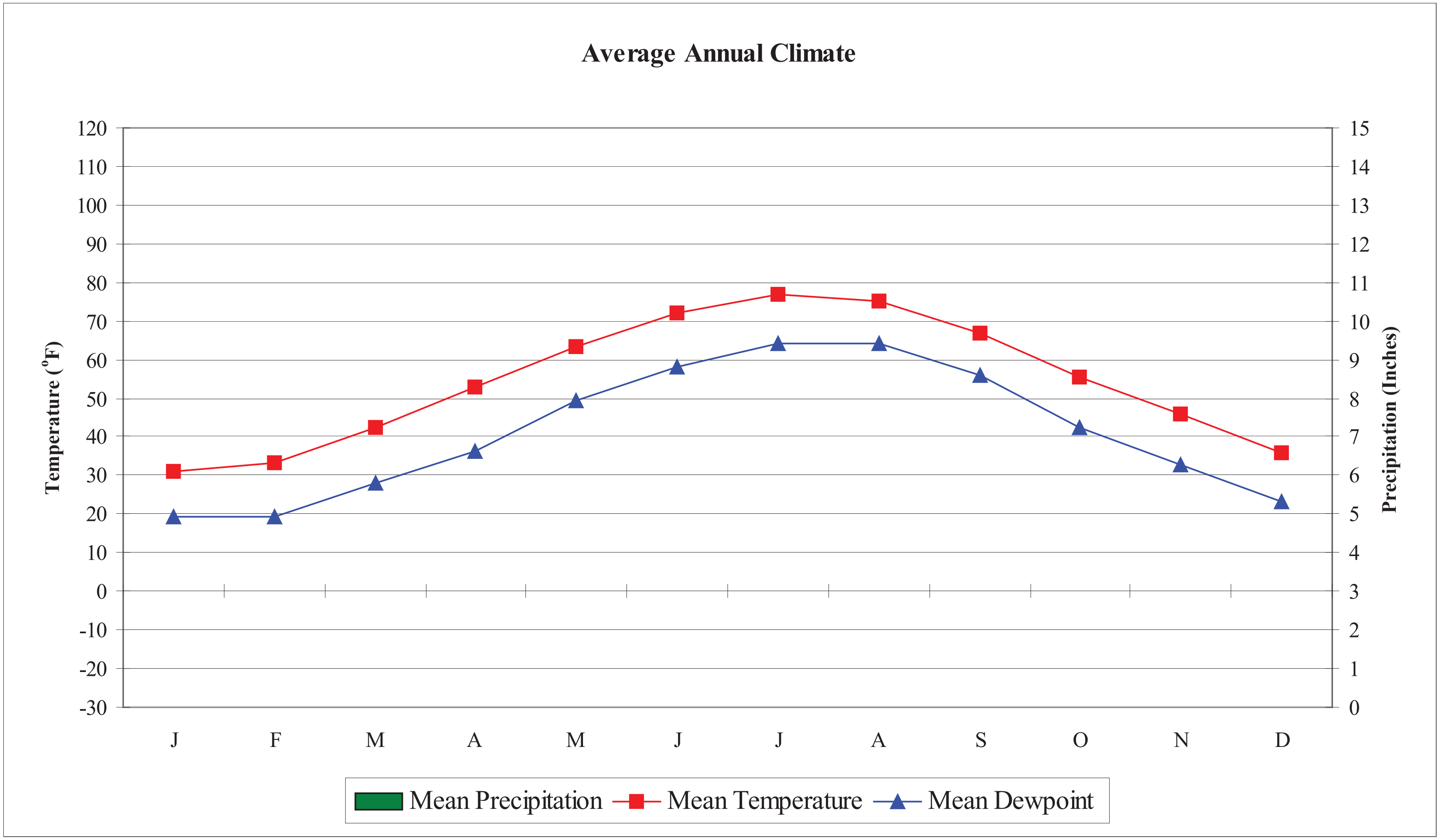
		Mean Coincident (Average) Values			
Dry Bulb Temperature (T)	**Design Value (^oF)**	Wet Bulb Temperature (^oF)	Humidity Ratio (gr/lb)	Wind Speed (mph)	Prevailing Direction (NSEW)
Median of Extreme Highs	97	78	117	11.9	W
0.4% Occurrence	93	76	109	11.0	W
1.0% Occurrence	90	75	105	10.7	W
2.0% Occurrence	87	73	100	10.6	W
Mean Daily Range	18	-	-	-	-
97.5% Occurrence	18	15	7	11.4	NW
99.0% Occurrence	13	11	5	11.9	NW
99.6% Occurrence	8	6	4	11.8	NW
Median of Extreme Lows	2	0	3	13.1	W
		Mean Coincident (Average) Values			
Wet Bulb Temperature (T_{wb})	**Design Value (^oF)**	Dry Bulb Temperature (^oF)	Humidity Ratio (gr/lb)	Wind Speed (mph)	Prevailing Direction (NSEW)
Median of Extreme Highs	81	90	141	9.8	W
0.4% Occurrence	78	87	128	10.0	WSW
1.0% Occurrence	77	86	125	9.9	WSW
2.0% Occurrence	75	83	117	9.6	WSW
		Mean Coincident (Average) Values			
Humidity Ratio (HR)	**Design Value (gr/lb)**	Dry Bulb Temperature (^oF)	Vapor Pressure (in. Hg)	Wind Speed (mph)	Prevailing Direction (NSEW)
Median of Extreme Highs	142	83	0.94	9.3	SW
0.4% Occurrence	136	83	0.90	8.8	WSW
1.0% Occurrence	128	82	0.85	8.5	WSW
2.0% Occurrence	120	80	0.79	9.4	W
Air Conditioning/		$T \geq 93^oF$	$T \geq 80^oF$	$T_{wb} \geq 73^oF$	$T_{wb} \geq 67^oF$
Humid Area Criteria	# of Hours	34	714	331	1052

Other Site Data

Weather Region	Rain Rate 100 Year Recurrence (in./hr)	Basic Wind Speed 3 sec gust @ 33 ft 50 Year Recurrence (mph)	Ventilation Cooling Load Index (Ton-hr/cfm/yr) Base 75^oF-RH 60% Latent + Sensible
7	3.1	110	1.1 + 0.6
Ground Water Temperature (^oF) 50 Foot Depth *	Frost Depth 50 Year Recurrence (in.)	Ground Snow Load 50 Year Recurrence (lb/ft^2)	Average Annual Freeze-Thaw Cycles (#)
56.9	N/A	N/A	56

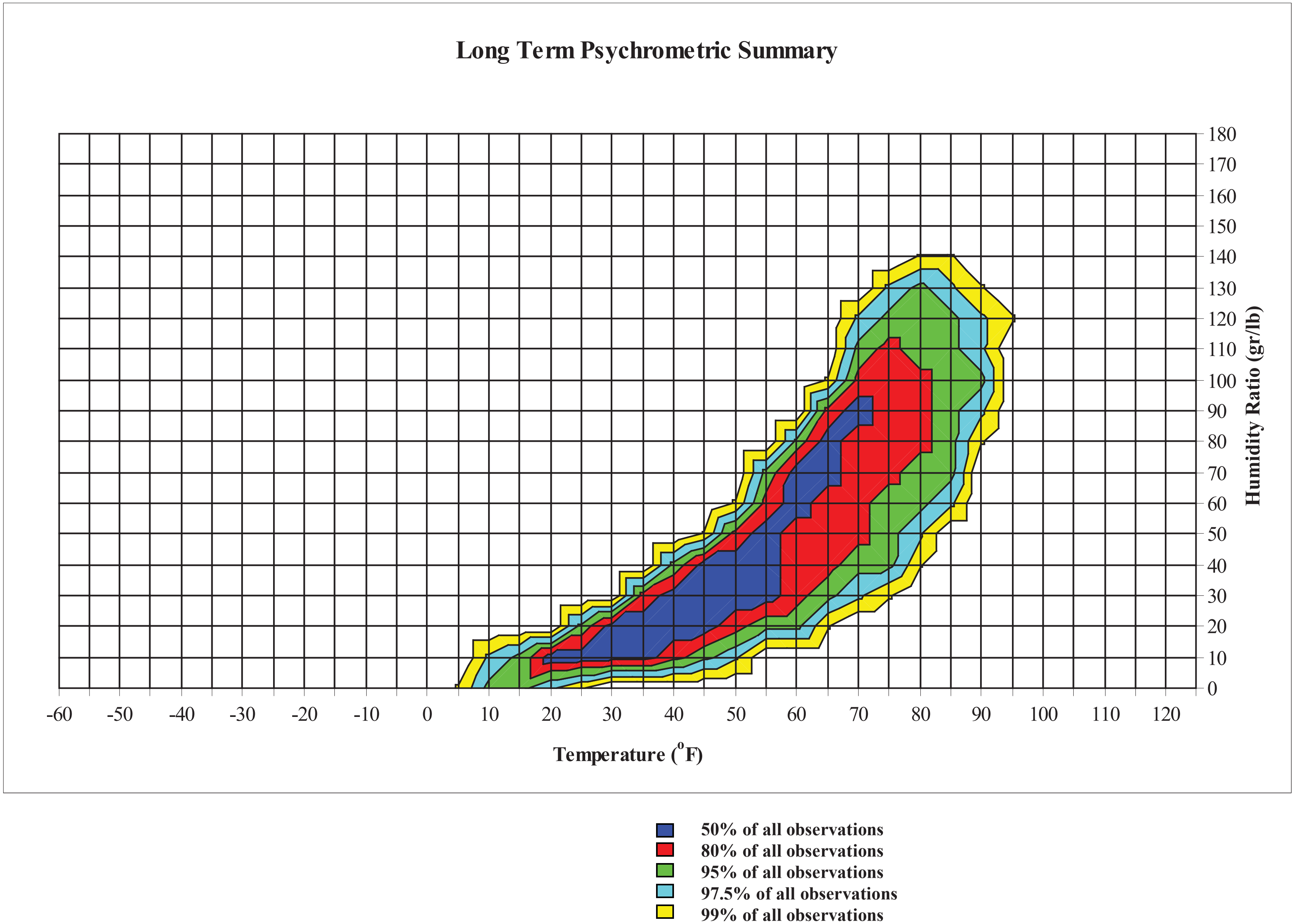
*Note: Temperatures at greater depths can be estimated by adding 1.5^oF per 100 feet additional depth.

TRENTON/MERCER NJ WMO No. 724095

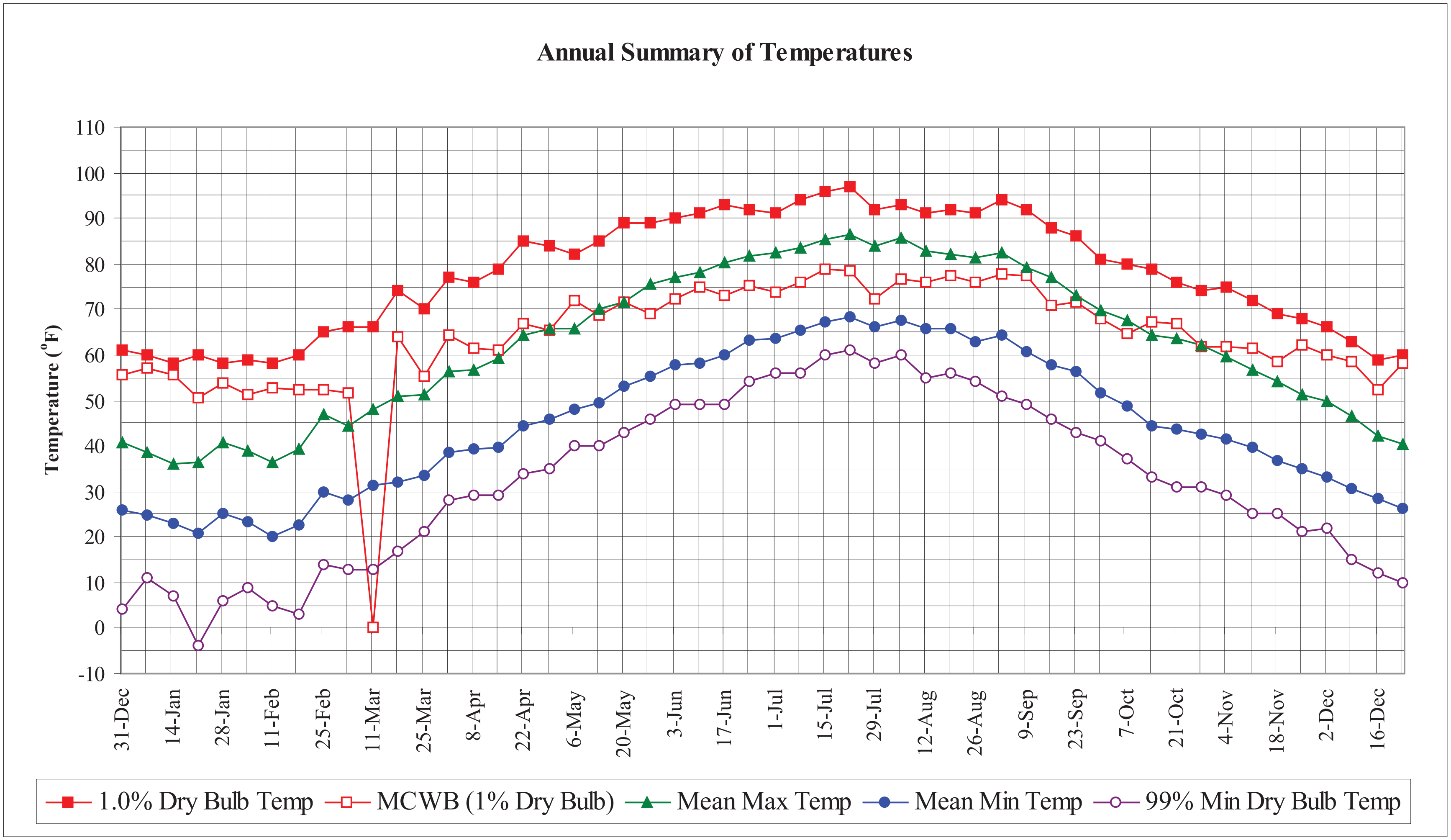


No Precipitation Data Available

TRENTON/MERCER NJ WMO No. 724095



TRENTON/MERCER NJ WMO No. 724095



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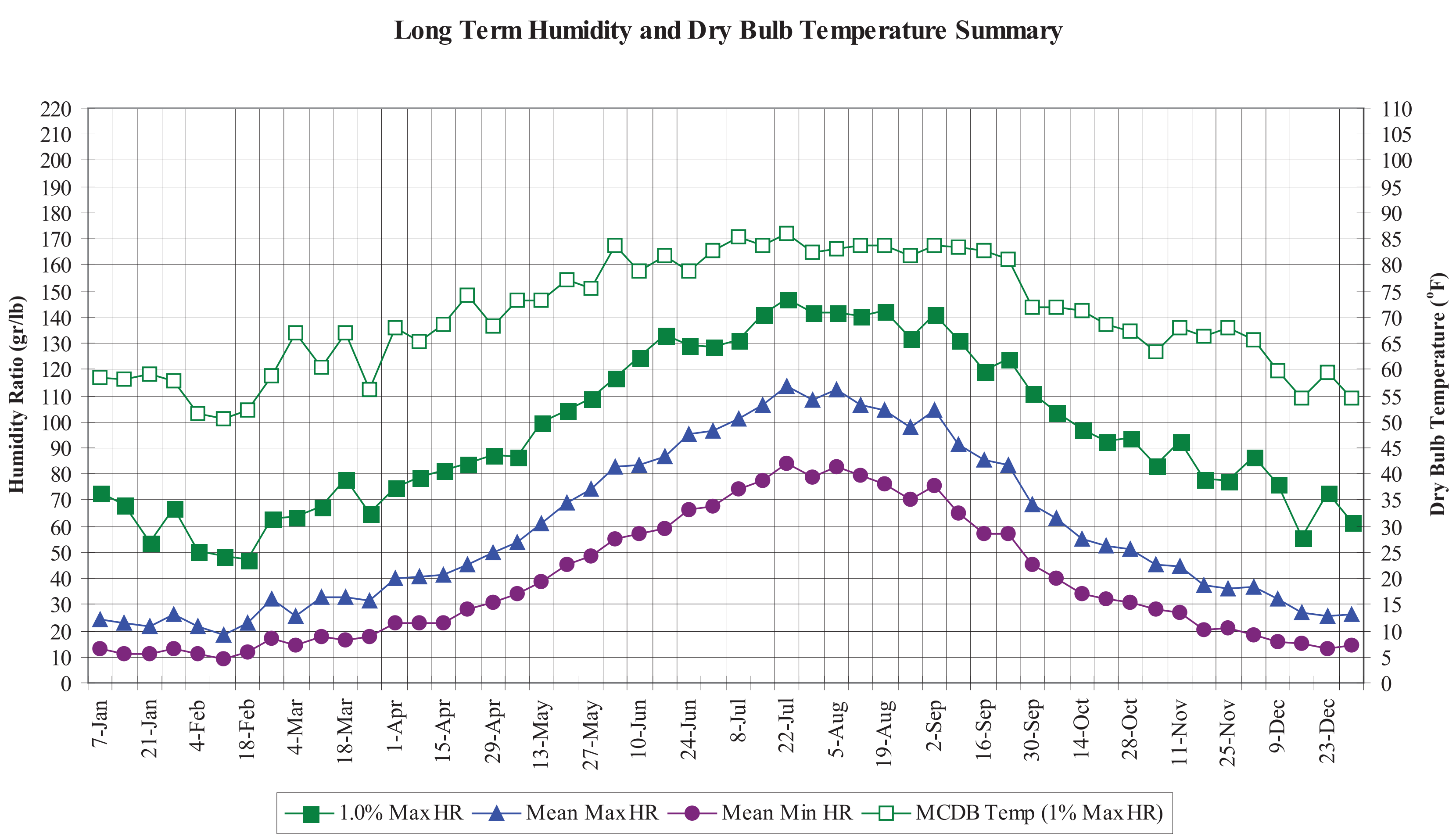

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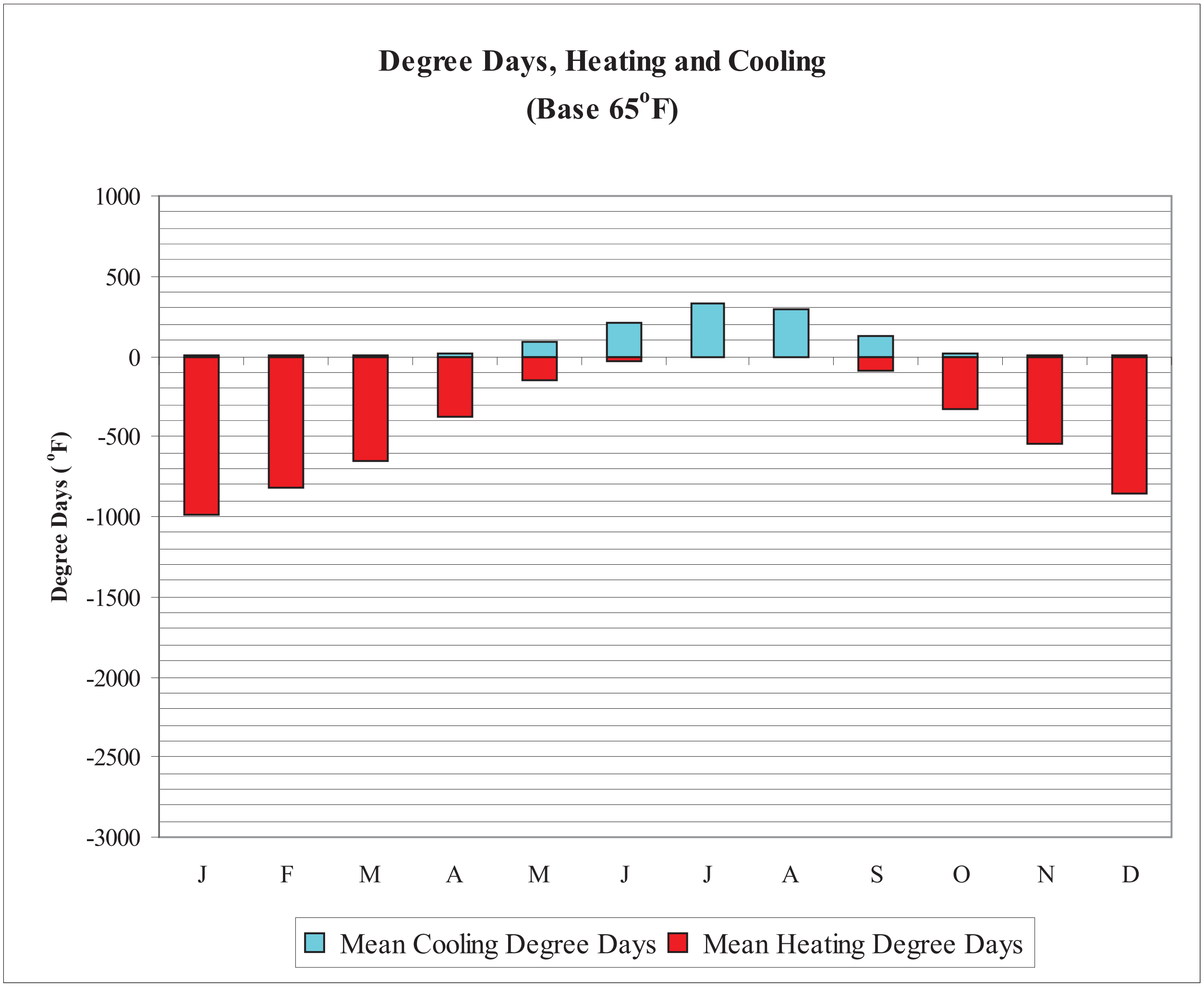
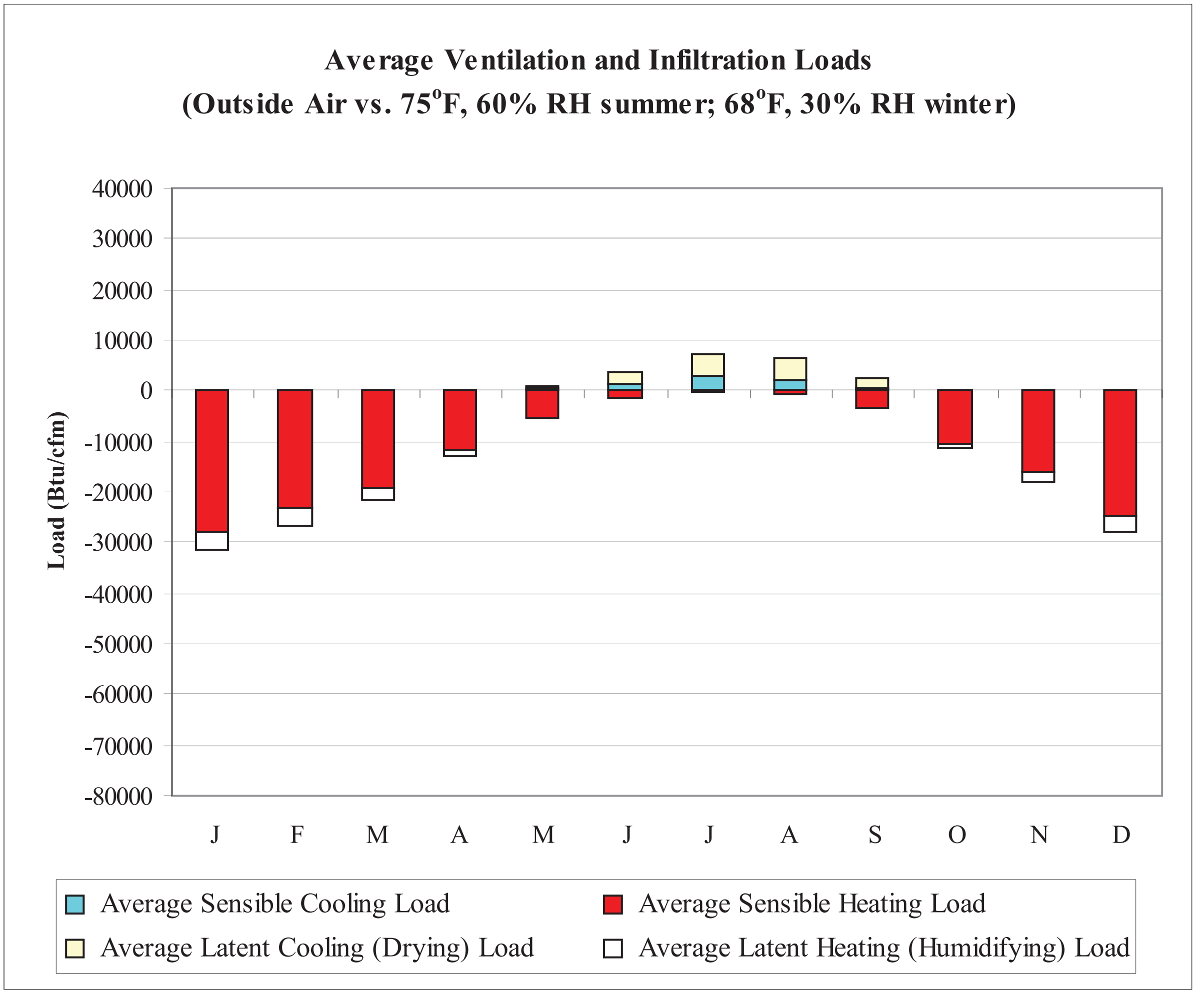


	Mean Cooling Degree Days (°F)	Mean Heating Degree Days (°F)
JAN	0	986
FEB	0	821
MAR	4	656
APR	21	376
MAY	85	151
JUN	214	29
JUL	329	6
AUG	288	11
SEP	131	85
OCT	23	326
NOV	4	539
DEC	0	862
ANN	1102	4848

TRENTON/MERCER NJ WMO No. 724095



	Average Sensible Cooling Load (Btu/cfm)	Average Sensible Heating Load (Btu/cfm)	Average Latent Cooling Load (Btu/cfm)	Average Latent Heating Load (Btu/cfm)
JAN	0	-27810	2	-3455
FEB	0	-23267	0	-3256
MAR	8	-19178	2	-2343
APR	90	-11765	28	-1169
MAY	469	-5436	531	-149
JUN	1462	-1346	2045	-5
JUL	2871	-356	4517	0
AUG	2063	-599	4458	0
SEP	684	-3358	1780	-19
OCT	42	-10538	202	-614
NOV	3	-16120	39	-1809
DEC	0	-24634	3	-3307
ANN	7692	-144407	13607	-16126

Average Annual Solar Radiation – Nearest Available Site

(Source: National Renewable Energy Laboratory, Golden CO, 1995)

City:	PHILADELPHIA
State:	PA
WBAN No:	13739
Lat(N):	39.88
Long(W):	75.25
Elev(ft):	30

Stn Type:	Secondary
SHADING GEOMETRY IN DIMENSIONLESS UNITS	
Window:	1
Overhang:	0.53
Vert Gap:	0.32

AVERAGE INCIDENT SOLAR RADIATION (Btu/sq.ft./day), Percentage Uncertainty = 11

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
HORIZ	Global	620	870	1200	1520	1760	1940	1890	1710	1380	1020	680	530	1260
	Std Dev	42	72	91	118	135	115	116	88	100	74	55	39	35
	Minimum	520	770	1010	1230	1530	1640	1580	1530	1180	880	560	430	1200
	Maximum	710	1080	1370	1740	2050	2220	2110	1850	1560	1150	800	610	1350
	Diffuse	310	420	550	700	840	880	870	760	610	450	330	280	580
Clear Day	Global	890	1240	1710	2190	2490	2590	2510	2240	1820	1340	940	780	1730
NORTH	Global	190	260	340	430	540	610	580	480	380	290	210	170	370
	Diffuse	190	260	340	430	500	530	520	460	380	290	210	170	360
Clear Day	Global	180	240	330	430	580	680	620	480	360	270	200	160	380
EAST	Global	420	570	740	900	970	1050	1030	970	820	650	450	370	740
	Diffuse	240	320	420	520	600	630	630	570	470	360	250	210	430
Clear Day	Global	680	870	1110	1310	1410	1430	1400	1310	1140	910	690	610	1070
SOUTH	Global	1000	1080	1070	950	830	790	820	940	1070	1150	990	900	960
	Diffuse	340	410	480	540	570	580	580	570	520	450	360	310	480
Clear Day	Global	1880	1930	1780	1410	1080	940	990	1240	1580	1810	1830	1800	1520
WEST	Global	430	560	730	880	970	1050	1030	960	820	650	450	370	740
	Diffuse	240	320	420	520	610	640	630	580	470	360	260	210	440
Clear Day	Global	680	870	1110	1310	1410	1430	1400	1310	1140	910	690	610	1070

Average Annual Solar Heat and Illumination – Nearest Available Site

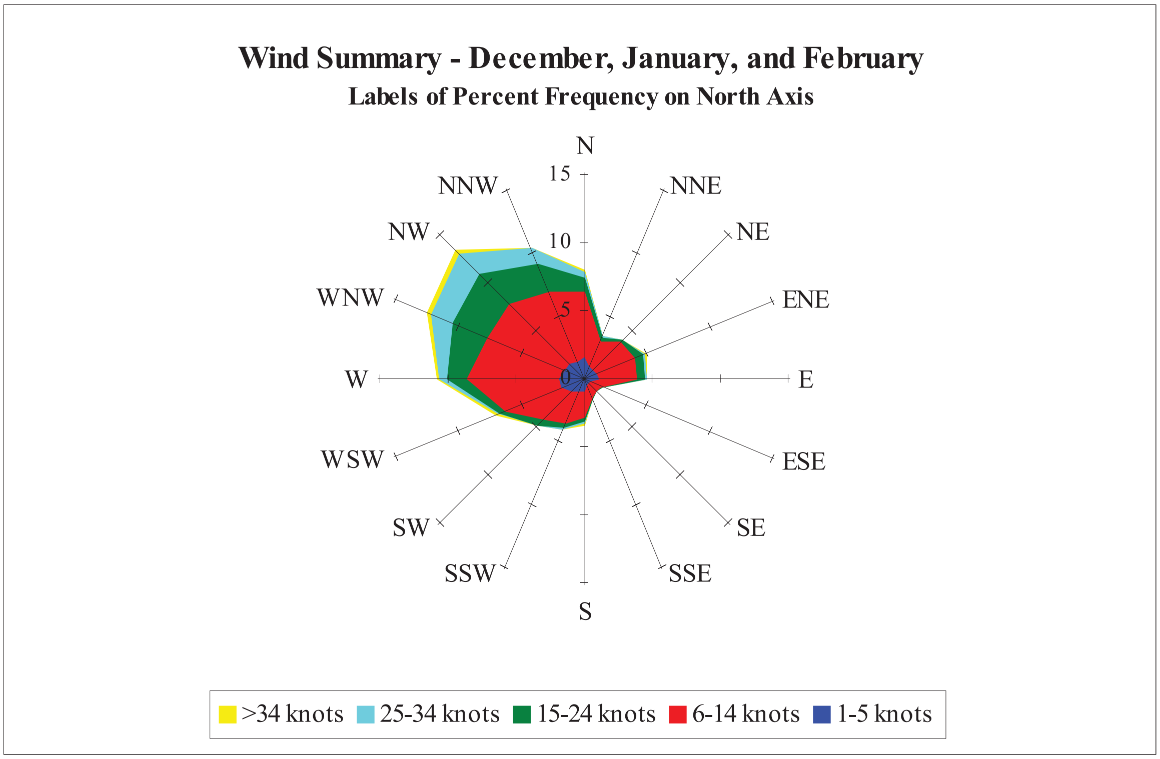
(Source: National Renewable Energy Laboratory, Golden CO, 1995)

AVERAGE TRANSMITTED SOLAR RADIATION (Btu/sq.ft./day) FOR DOUBLE GLAZING, Percentage Uncertainty = 11

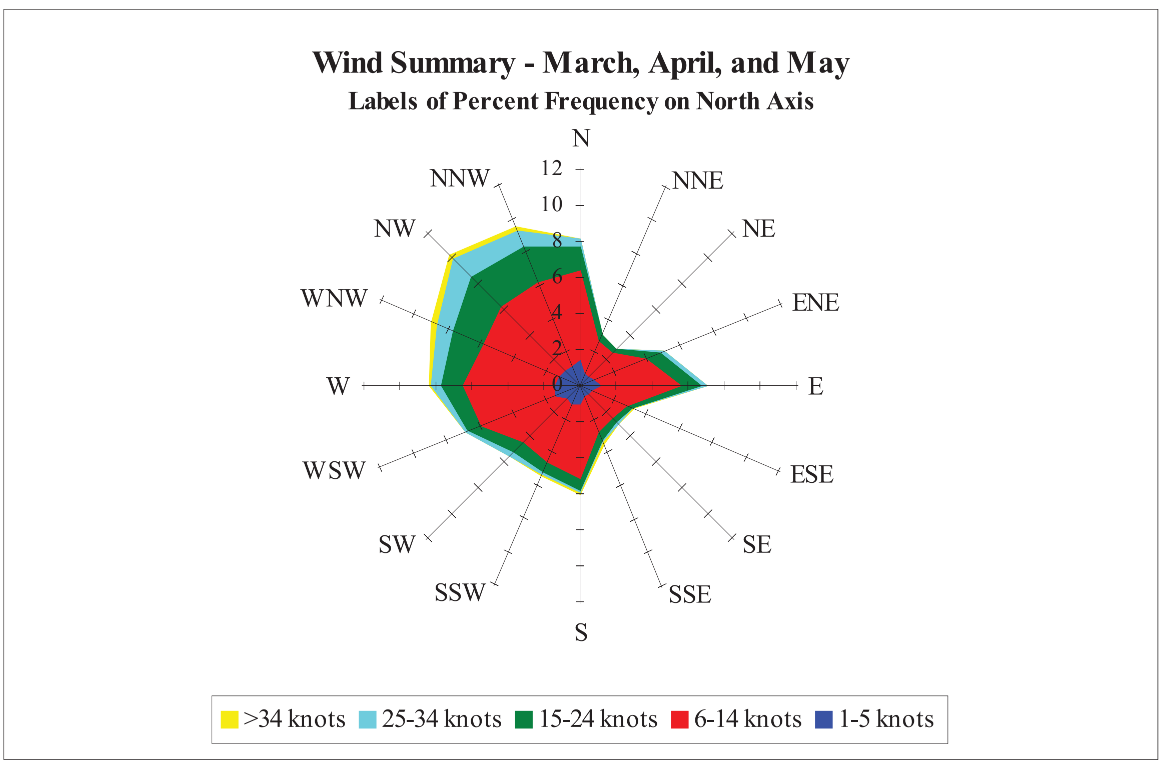
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
HORIZ	Unshaded	400	600	850	1090	1270	1410	1370	1240	990	710	450	340	890
NORTH	Unshaded	130	180	240	300	360	400	380	330	260	200	140	120	250
	Shaded	120	160	210	260	320	350	340	290	230	180	130	100	220
EAST	Unshaded	290	400	520	640	690	740	730	690	580	450	310	250	520
	Shaded	260	350	460	550	580	620	610	580	500	400	280	230	450
SOUTH	Unshaded	750	790	740	620	520	480	500	600	730	830	740	680	660
	Shaded	730	730	590	410	350	360	360	390	520	730	710	660	540
WEST	Unshaded	300	390	520	620	690	740	730	680	580	450	310	250	520
	Shaded	270	350	450	530	590	630	620	580	500	400	280	220	450

AVERAGE INCIDENT ILLUMINANCE (klux-hr) FOR MOSTLY CLEAR AND MOSTLY CLOUDY CONDITIONS, Percentage Uncertainty = 11

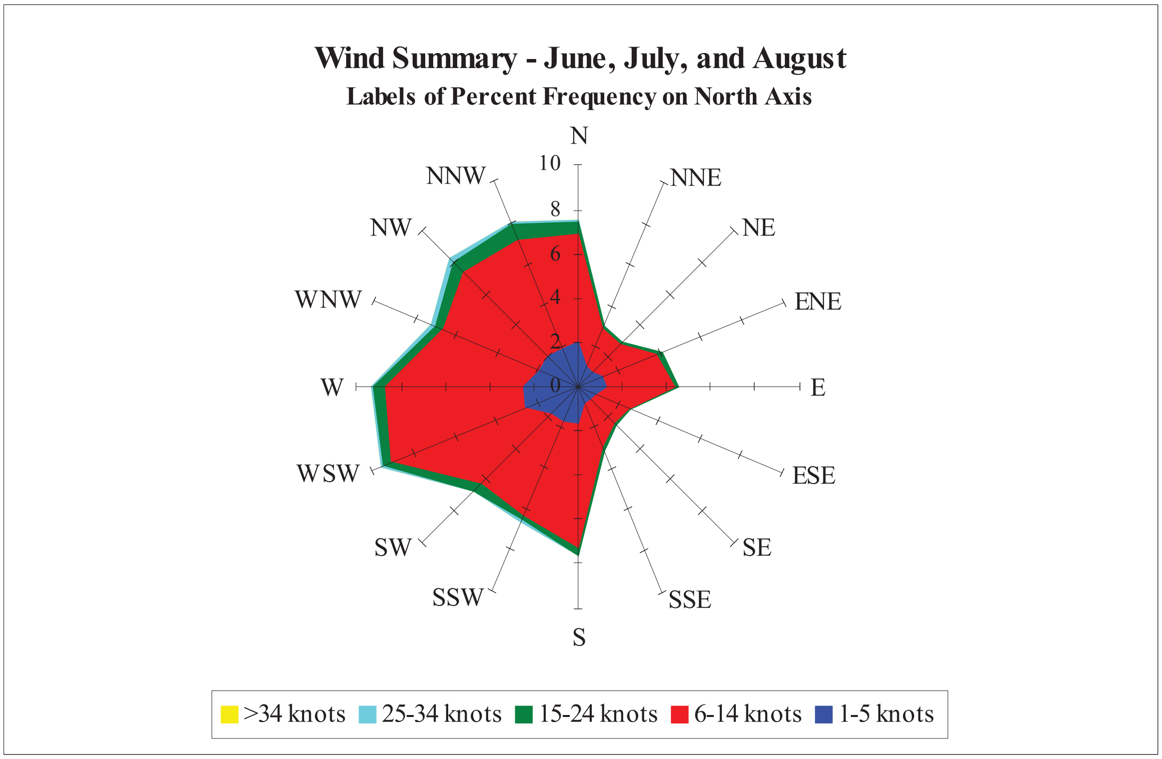
		March					June				
		9am	11am	1pm	3pm	5pm	9am	11am	1pm	3pm	5pm
HORIZ.	M.Clear	39	71	80	63	25	47	83	100	94	66
	M.Cloudy	22	43	48	37	15	28	55	69	66	44
NORTH	M.Clear	10	14	15	13	8	18	17	17	17	16
	M.Cloudy	9	15	16	13	6	13	18	20	19	15
EAST	M.Clear	72	55	15	13	8	75	71	30	17	16
	M.Cloudy	25	29	16	13	6	31	42	26	19	15
SOUTH	M.Clear	39	73	82	64	25	12	33	47	42	21
	M.Cloudy	17	35	40	30	11	11	25	35	32	17
WEST	M.Clear	10	14	24	66	61	12	17	17	53	76
	M.Cloudy	9	15	19	31	20	11	18	20	38	42
M.Clear	(% hrs)	36	33	31	32	35	40	39	37	35	37
		Sept					Dec				
		9am	11am	1pm	3pm	5pm	9am	11am	1pm	3pm	5pm
HORIZ.	M.Clear	28	66	83	76	45	14	40	45	27	2
	M.Cloudy	16	40	53	50	28	8	22	26	16	2
NORTH	M.Clear	9	14	16	16	12	5	10	10	8	1
	M.Cloudy	7	14	18	16	11	4	9	10	7	1
EAST	M.Clear	62	68	27	16	12	39	37	10	8	1
	M.Cloudy	20	33	22	16	11	10	16	10	7	1
SOUTH	M.Clear	21	57	75	67	37	36	79	85	58	5
	M.Cloudy	10	29	42	39	20	10	27	31	19	1
WEST	M.Clear	9	14	16	53	71	5	10	22	46	7
	M.Cloudy	7	14	18	33	31	4	9	13	16	2
M.Clear	(% hrs)	43	45	43	39	40	33	32	30	31	36



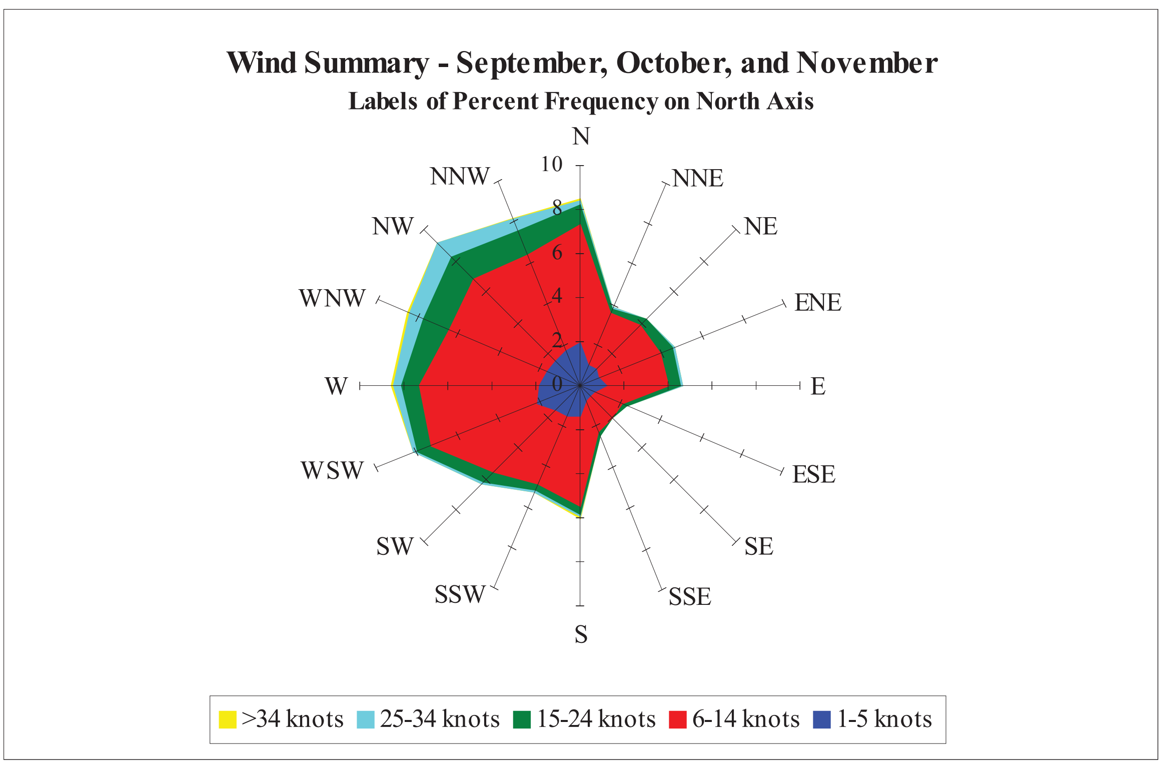
Percent Calm = 6.00



Percent Calm = 4.69



Percent Calm = 7.20



Percent Calm = 7.35

Appendix E

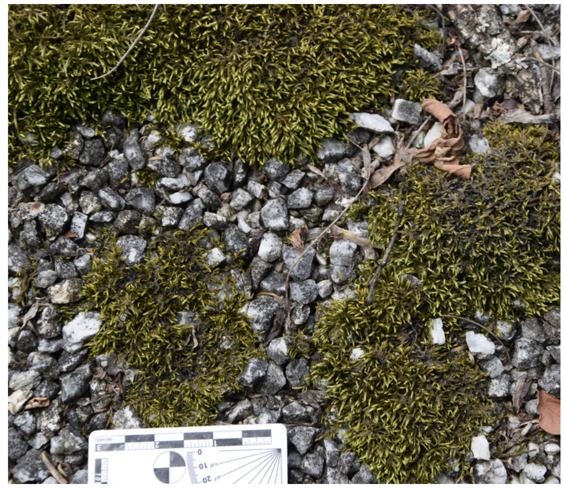
Conditions Glossary

Roofing system

Conditions

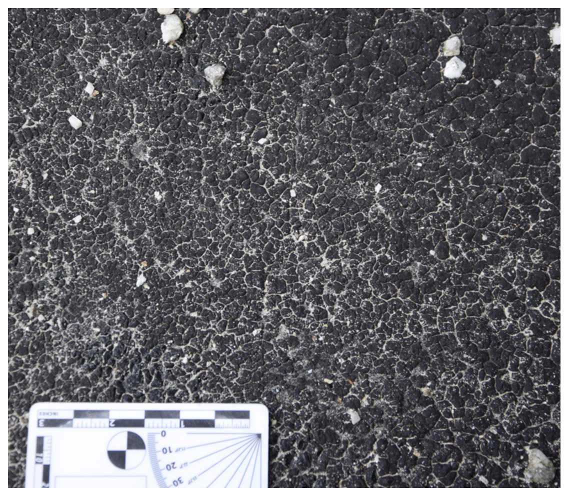
Biological Colonization

Presence of mosses and lichens on the roof slope contributing to moisture retention.



Asphalt Alligatoring

Asphalt exposed layer is deteriorated as a result of its exposure to UV radiation.



Clogged gutters

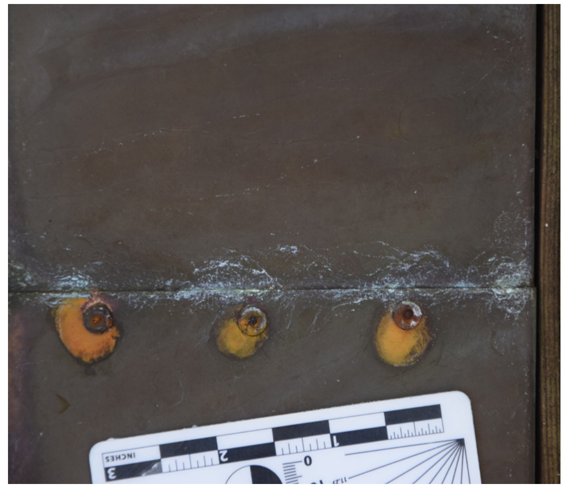
Presence of marble chips and leaves accumulated in the base of gutters contributing to poor drainage and water overflow.

Roofing system

Conditions

Corrosion

Greenish-blue corrosion occurs in the flashing joints due to water retention and redox reactions.



Impact Damage

Elements show distress due to mechanical impact of fallen branches.

Open Flashing

Sections of copper sheets are out of plane because of lack of adhesion or insufficient adhesion.

Roofing system

Conditions

Active Leak

Moisture stains and wet surface from water seepage through the roofing system.

Plywood Deformation

Plywood board is bent and not flush with the contiguous boards.

Plywood Checking

Multiple hairline cracks or slightly open parallel splits of different length.

Conditions

Rib Crack

Single crack visible in rib joint.

Rib checks

Checks limited to the lower middle section of the rib.

Moisture Stain

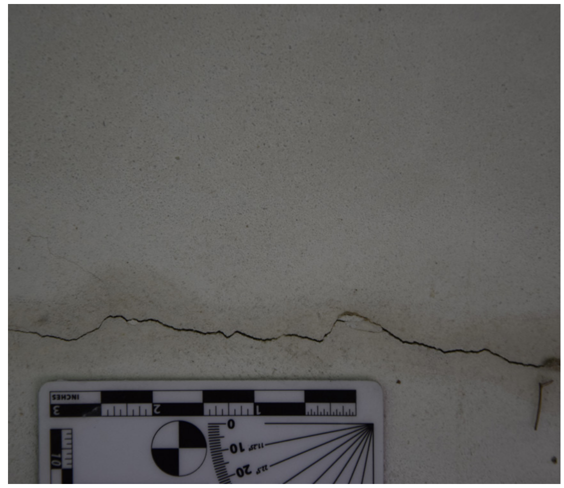
Color alteration in the ribs because of exposure to moisture. Water source can be a leak in the past, exposure during construction, or water vapor that condesates.

Rendered Concrete Block Masonry Wall

Conditions

Crack

Cracks of variable lenght with a width between 1/32 and 1/16 inch, primarily longitudinal along the bedding joint. It can be accompanied by calcium carbonate deposits.

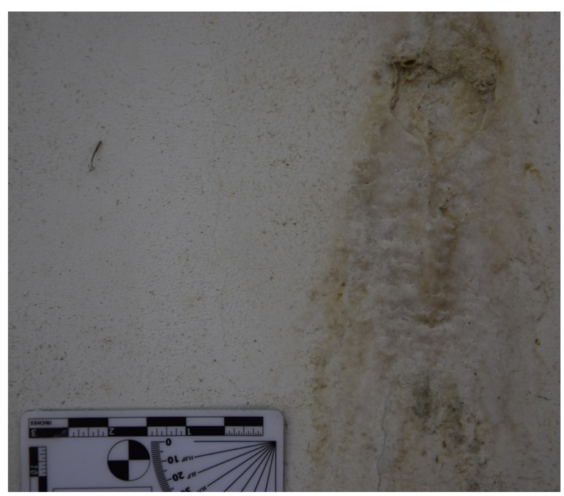


Hairline Crack

Cracks in the stucco surface having widths so small as to be barely perceptible. Orientation may vary and they can intersect other cracks forming a pattern.

Mineral Accretion

Salts transported by water has evaporate and crystallized on the stucco surfaces forming mineral deposits in association with a reddish bronw stain.



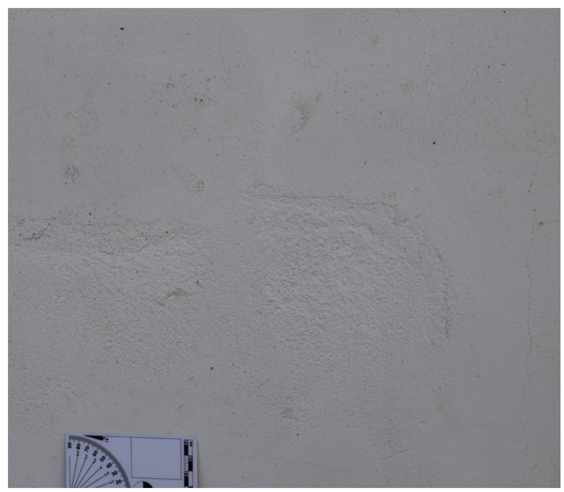
Conditions

Soiling

Water splash deposited soil particles upon the rendered surfaces creating a thin brown film disrupting the aesthetics qualities of the white stucco.

Superficial Erosion

Increased surface roughness due to moisture infiltration and salt crystallization. Surfaces constrast with the smoother sourrounding surfaces.



Previous Repair

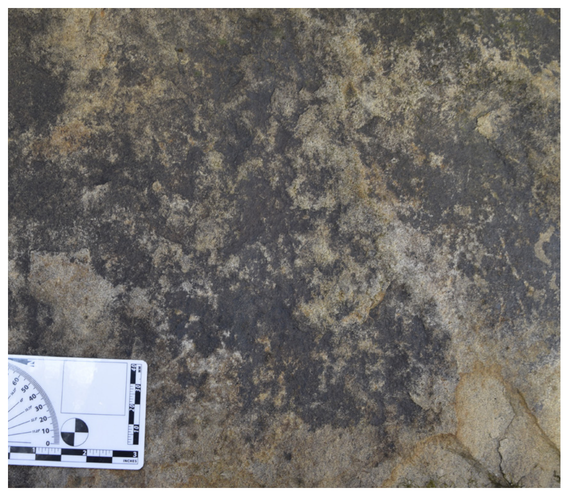
Repair of eroded and cracked surfaces with a white cementitious material that shows a coarse-grain texture.

Efflorescence

Generally whitish, powdery salts crystallized on the surface. Efflorescences are generally poorly cohesive and commonly soluble salt. This condition has been observed in the exterior and interior walls.

Soiling

Deposit of a very thin layer of particles giving a dirty appearance to the stone surface. It may be a direct effect of earlier biological colonization with algae.



Insect Nest

Mud dauber wasps have constructed their nest on the stone surface. Nests are also localized on other substrates in the other areas of the building.

Flaking

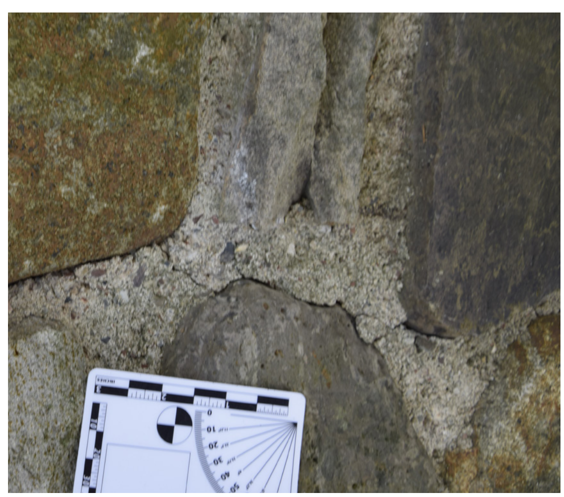
Scaling in thin flat or curved scales. The detachment is located near to the stone surface.

Blistering

Surface erupts into blisters and crumbles away leading to a loss of stone surface.

Hairline cracks

Thin cracks between mortar joints and stone units.



Biological Colonization

Presence of mosses, lichens, and algae on the stone masonry.

Hairline Crack

Cracks in the concrete elements having widths so small as to be barely perceptible. Hairline cracks show a variety of direction and can be accompanied by efflorescence or rust staining.

Rust Staining

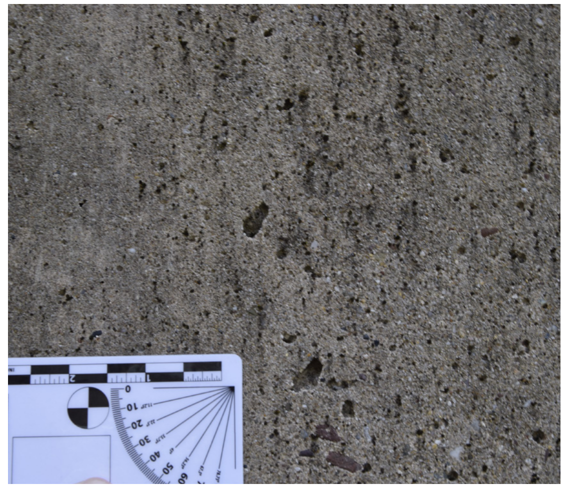
Rust brownish red stains in a limited area of the concrete surface as a consequence of moisture intrusion and rebar corrosion.

Honeycombing

Voids left in concrete due to poor mixing of the aggreagate and vibration during the placing process.

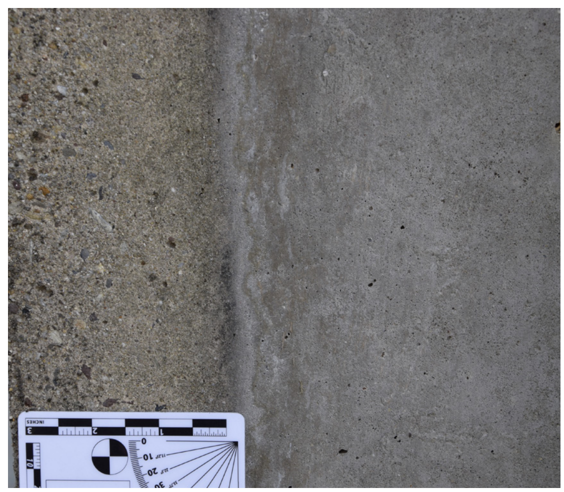
Bugholes

Small regular or irregular cavities as a result of entrapped bubbles during the placing process. Overall, they do not exceed 5/8 inch in diameter.



Superficial Erosion

Overall rough surfaces due to exposure to rainwater, which has dissolved the outer layer of the cement paste leaving the aggregate particles exposed.

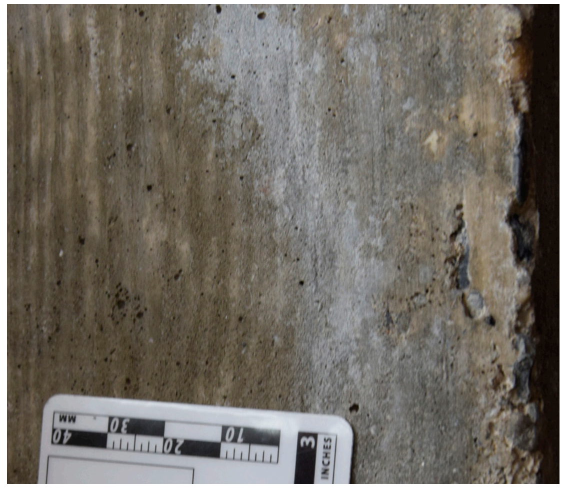


Moisture Stains

Discoloration of the concrete surface as a consquence of temporary wetting episodes.

Efflorescence

A whitish deposit of salts crystallized on the concrete surface precipitated by carbonation or evaporation.



Biological Colonization

Presence of algae covering surfaces exposed to permanent moisture or regular wetting episodes.

Impact Damage

Mechanical damage on the outer surface of the concrete.

Ferrous materials

Installation of metallic elements by insertion in a concrete element.

Scratches

Mechanical damage to the outer surfaces of the concrete thus damaging the fragile woodprint pattern.

Stains

Color alteration due to cleaning and refinishing procedures in the loft.

Rot

Areas of wood, showing color alteration, that have been attacked by fungus. These areas are soft and easily penetrable with an awl.

Checking

Longitudinal openings extending along the length of the wood member facitilitating moisture infiltration. Structural stability appears not to be comprosised though.

Moisture Stains

Uneven color alteration because of wetting episodes. Wood may be wet or dry.

Natural Weathering

Wood surfaces showing the symptoms of slow degradation from a combination of natural factors: sunlight, moisture, temperature, chemicals, suspended particles carried by wind, and biological agents.

Scratches

Damages from animal activity, probably squirrels.

Previous repair

Holes perforated by woodpeckers repaired with the use of a brown epoxy resin.

Wood elements

Conditions

Woodpecker damage

Woodpeckers, probably attracted by carpenter bee activty, pecked holes on wood.

Fungal growth

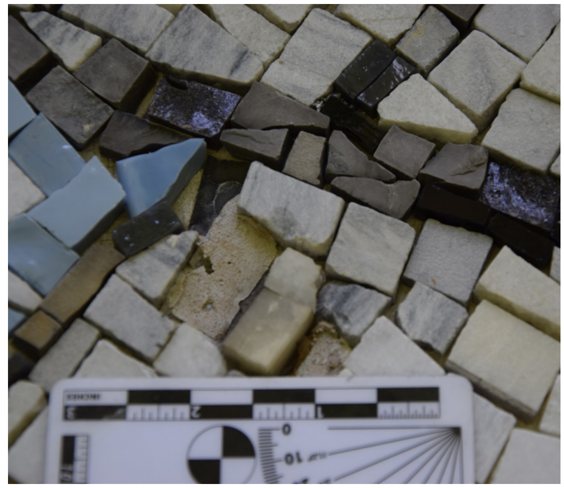
Fungal growth on the undeside of the north railing on the terrace at the Arts Building. Photo by Ron Anthony.

Mosaic

Conditions

Missing Tessera

Single or multiple tesserae have detached because of lack of adhesion between the tesserae and the substrate.



Granular Disintegration

Eroded and detached surface of tesserae.

Color Alteration

Discoloration due to the use of epoxy resin to adhere the tesserae and hide the screw heads fastening the mosaic to a wood substructure.

Mosaic

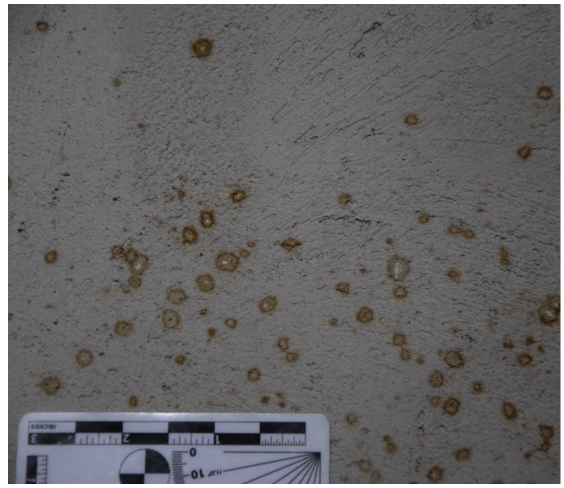
Conditions

Biological Colonization

Microflora and soiling covering the lower section of the mosaic panels.

Spotting

Circular staining that might be related to the oxidation of metallic components in the Structolite™ or to an unknown chemical reaction between constituents.



Efflorescence

Chiefly whitish powdery deposit of salts crystallized on the plaster surface.

Moisture Stains

Color alterations of the surfaces caused by active leakage or past moisture infiltration.

Flooring Materials

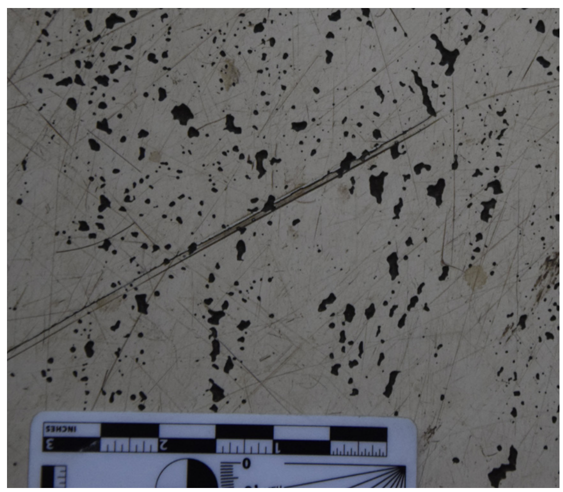
Conditions

Fire Damage

Vinyl flooring has been damage by fire in the proximity to the fireplace hearth.

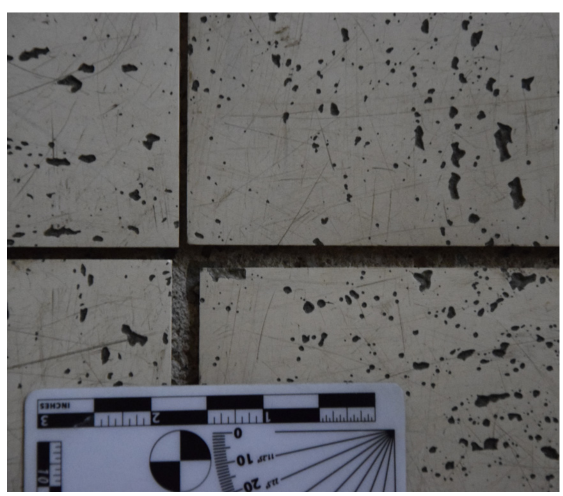
Wear

Scratches and superficial damage from visitation and use are visible on the vinyl flooring.



Tile shrinkage

The vinyl flooring presents a contraction in comparison to their original dimension due to sunlight exposure.



Stains

Both stone pavement and vinyl flooring show stains as a consequence of catering activities. Also, it was visible stains related to water leaking from the wooden planters, which are usually placed indoors during the cold months.

Missing & Failing Joints

Joints in the Cave stone pavement show loose and are missing in some locations.

Scaling

Detachment of stone as a scale parallel to the stone surface. Presumably, the stone cannot withstand the high temperatures of a fire. Cracks are also visible.

Appendix F

Material Characterization

GRAVIMETRIC ANALYSIS OF ARTS BUILDING'S CHIMNEY MORTAR

New Hope, Pennsylvania

Prepared by Araba Prah, Nicole Declet, and Cesar Bargues

1. INTRODUCTION

A sample of joint mortar taken from the south elevation of the chimney at the Arts Building in New Hope, Pennsylvania was analyzed by gravimetric analysis in order to determine approximate ratios of aggregate, binder, and fines relative to the overall mortar. Results of this analysis will eventually inform the type of aggregates to use, as well as the choice of a compatible replacement mix for repair and repointing of the stone masonry as a part of the training program for Summer 2016.

Essentially, mortars are composite materials comprised of binders, aggregates, water, and additives in various proportions. Gravimetric analysis of any mortar presumes that the bulk sample can be separated by mechanical and chemical action in order to estimate the ratios of these main constituents, to characterize the aggregates, as well as to determine possible type of binding agent (clay, gypsum, lime, hydraulic limes, natural and artificial cements).

Generally, the application of acid to the mortar samples will produce the acid digestion of all soluble components, while those constituents not susceptible to this process will remain. This can be chemically defined as the reaction of carbonaceous materials with the hydrochloric acid that produces chloride salts, water, and carbon dioxide. The soluble materials together with the remaining fines are believed to represent the binder. The ratio of binder and aggregates can be quantitatively measured by weighing the samples before and after acid digestion. The insoluble materials, aggregates and fines, can be separated by sieve analysis and their physical characteristics determined by qualitative and quantitative analysis, which include particle size, shape, color, and distribution.

The gravimetric analysis has proved to be a useful tool to replicate and specify compatible mortar replacements; however, the limitations of this technique need to be considered before its application. Calcareous aggregates and some silicates will also be dissolved by the action of hydrochloric acid, which, consequently, will affect the ratio of binder aggregate and will offer a misleading result. Other characteristics, such as the original water/binder proportion, the mixing and placing method, the rate of drying, and the cleanliness and condition of the aggregates, cannot be determined by implementing this methodology. Finally, as this analysis was performed for a particular sample form the chimney mortar, it is not applicable for the rest of the stone masonries present at the Arts Building and other construction on the site.

2. METHODOLOGY

The mortar analysis and characterization was performed following the methodology established by the Architectural Conservation Laboratory at the University of Pennsylvania; particularly, "Experiment 12: Gravimetric Analysis of Mortars (Acid Digestion Method)" and "Experiment 01: Characterization of Granular Samples by Sieve Analysis", both in accordance with ASTM, professional and scholar recommendations.

On June 6, 2016, two members of the Architectural Conservation Laboratory took representative samples of the south and east chimney walls (about 100 grams). Samples were identical in color, texture, and hardness. No previous repair campaign was observed on site, and it is possible to conclude the locations relate to the original fabric as built between 1964 and 1967.

Half of the original sample, about 54 grams, was powdered using a clean ceramic mortar and pestle. The other half was kept separately for further examination and comparison with new mortar samples prepared for a possible repair project. A few traces of biogrowth and soiling could not be fully removed prior to analysis. It is probable this would have an impact on the color of the soluble. 14% hydrochloric acid was added to the sample in order to dissolve the binder and separate the fines from the aggregates. Throughout the experiment great care was taken to avoid measurement deviations and to ensure environmental conditions, such as temperature and humidity, could not affect the experiment. Precautions included keeping the ground sample and the resulting aggregates and fines in the oven and the desiccator throughout the experiment, which was performed in the span of a week. This would warrant comparable weights and minimum experimental error.

Resultant aggregate and fines were observed and characterized with the aid of a stereo binocular microscope and compared with sands in the reference library held at the Architectural Conservation Laboratory. Lastly, sand was sieved to determine the particle size distribution. Traces of iron were observed after acid digestion.

3. DATA AND OBSERVATIONS

Image Of George Nakashima's Arts Building Chimney Mortar Bulk Sample

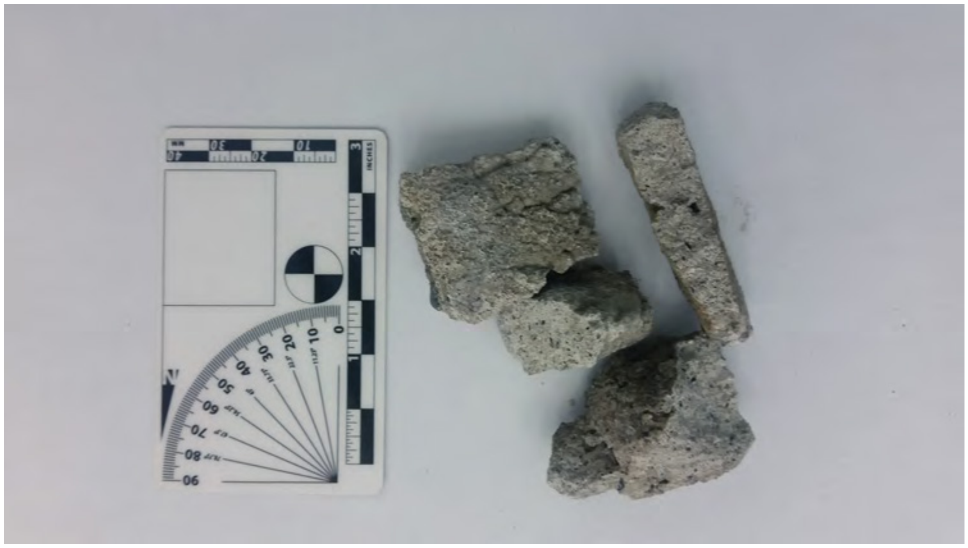


Image Of Ground Mortar Bulk Sample Prior To Acid Digestion

Table 5.1 - MORTAR COMPONENTS BY ACID DIGESTION									
	Dry powdered sample + container	Container	Dry powdered sample	Filter paper	Filter paper + dry fines	Dry Fines	Dry aggregate beaker	Dry aggregate + beaker	Dry aggregate
	M_0	M_C	M_1	M_2	M_3	M_F	M_{C1}	M_{C2}	M_4
Sample	318.91	264.84	54.07g	3.91	7.34	3.43	264.84	299.65	34.81

Site / Sample ID	NAKA_chimney mortar_south
Sampled by	Cesar Bargues and Araba Prah
Sampled on	6/6/16
Analyzed by	Cesar Bargues and Araba Prah
Analyzed on	6/8/16
Description	Mortar sample from Art Building chimney (exterior) above roof line
Appearance	Some soiling present on surface Aggregates of different colors visible
Snap Strength	Not possible to snap
Layering	Not visible
Bulk Color (Munsell)	2.5Y 8/1 white/light gray
Streak (Munsell)	2.5Y 8/1 white
Hardness (Mohs)	#4
Magnetic	None
	Sample fizzed when HCL solution was applied

NOTES & CALCULATIONS							
	Organics	Magnetic	Reaction	Color	Weight (g)	% total weight	Weight ratio
FINES	no	no	n/a	2.5 Y 7/2 light gray	3.43	6.12%	1:10
SOLUBLE	n/a	n/a	reaction with release of CO_2	cloudy, greenish	17.83	31.8%	3:10
AGGREGATE	no	YES	n/a	2.5 Y 7/2 light gray	34.81	62.08%	6:10

Table 5.2 -							
SIEVE TEST DATA							
ASTM Sieve Number	**Screen Size (µm)**	**Mass of container (g)**	**Mass of sample & container (g)**	**Mass retained (g)**	**Percent mass retained**	**Percent on or above**	**Percent Passing**
		M_c	M_2	M_r (M_2 - M_c)	$\%M_r$ (M_r/M_s) *100%	$\%M_{rt}$ Σ $\%M_r$ (on or above)	$\%M_{pt}$ 100% - $M_{rt}\%$
8	*2360*	1.78	3.37	1.59	4.58	4.58%	95.42%
16	*1180*	1.72	5.35	3.63	10.45	15.03%	84.97%
30	*600*	1.73	7.88	6.15	17.71	32.74%	67.26%
50	*300*	1.76	13.6	11.84	34.09	66.83%	33.17%
100	*150*	1.74	9.77	8.03	23.12	89.95%	10.05%
200	*75*	1.89	4.33	2.44	7.03	96.98%	3.02%
PAN	*1*	1.72	2.77	1.05	3.02	100.00%	0.00%

Table 5.3					
AGGREGATE CHARACTERIZATION AFTER ACID DIGESTION					
SIEVE #	**SIZE (µm)**	**SPHERICITY**	**ROUNDNESS**	**SORTING**	**COLOR**
8	2500-7000	Medium	Angular to subangular	fair	2.5Y 6/2 Gray
16	1180-2360	Low	Very angular to angular	Well	2.5 Y 7/2 Light gray
30	600-1180	Low	Very angular to angular	Well	2.5Y 8/1 White
50	300-600	Low	Very angular to angular	Well	2.5 Y 7/1 Light gray
100	150-300	Medium	Very angular to angular	Well	2.5 Y 7/1 Light gray
200	75-150	Medium	Very angular to angular	Well	2.5 Y 7/1 Light gray
Pan	Less than 75	Medium	Very angular to angular	Well	2.5 Y 7/1 Light gray
Fines	Less than 75	Medium	angular	Well	2.5 Y 7/1 Light gray

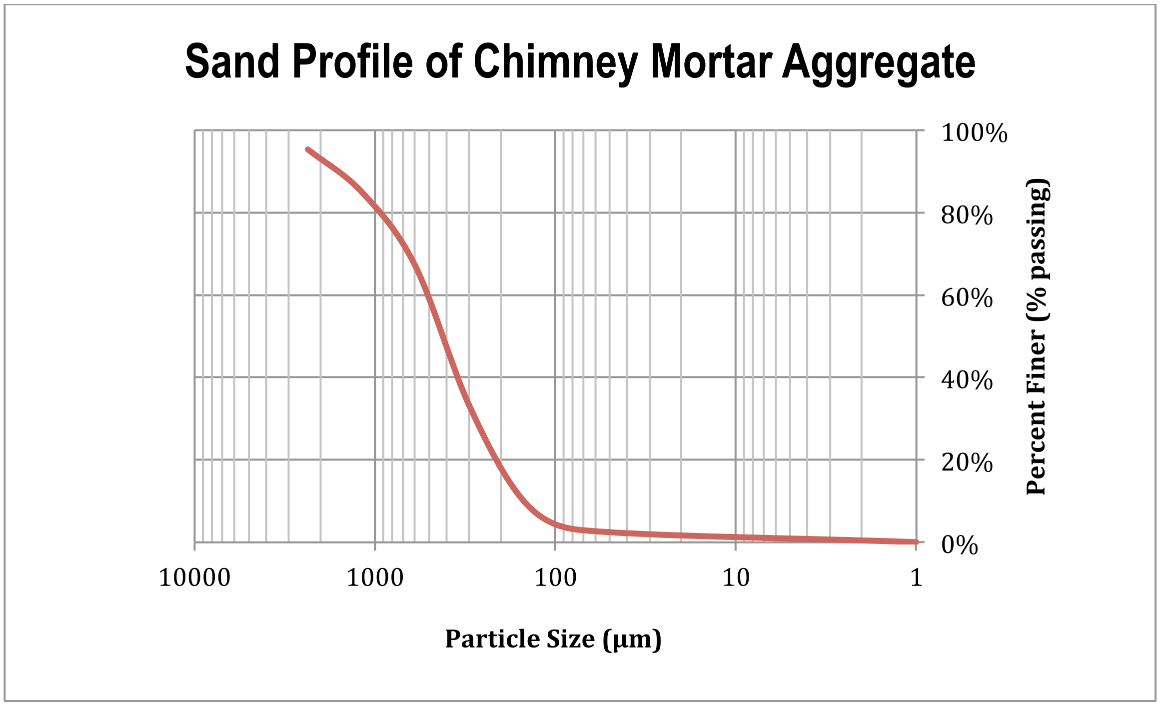
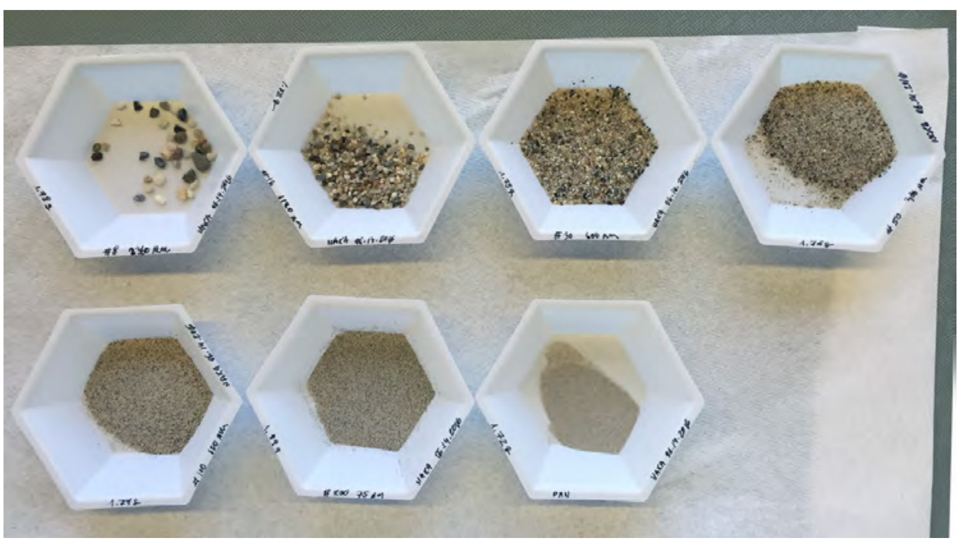


Image Of George Nakahima's Arts Building Mortar Aggregate After Sieving



5. DISCUSSION AND CONCLUSIONS

The experimentally determined ratios of aggregate to binder for the George Nakashima's Arts Building mortar was characterized to be approximately 1:10 fines, 3:10 soluble, and 6:10. The reaction of the 14% hydrochloric acid with the powdered mortar sample confirms the existence of certain concentration of calcium carbonate, while the visual observation of a freshly broken piece of the bulk sample as well as its hardness suggests that the binder was a combination of lime and, probably, white cement portland.

According to the results, the following is a list of three sands selected from the Architectural Conservation Sand Library to prepare mock-up mortar samples:

i. Superior Rock Products: Mason Sand 77
ii. Hanson Aggregates Inc.: Type A Concrete Sand
iii. Hanson Aggregates Inc.: Mason Sand C-144

Of these three sands, the mix prepared with Hanson Aggregates Inc. Mason Sand C-144 proved the appropriate match for the repair work to be conducted at the chimney stone masonry and crown.

Image Of The Mortar Sample Prepared With Mason Sand C-144

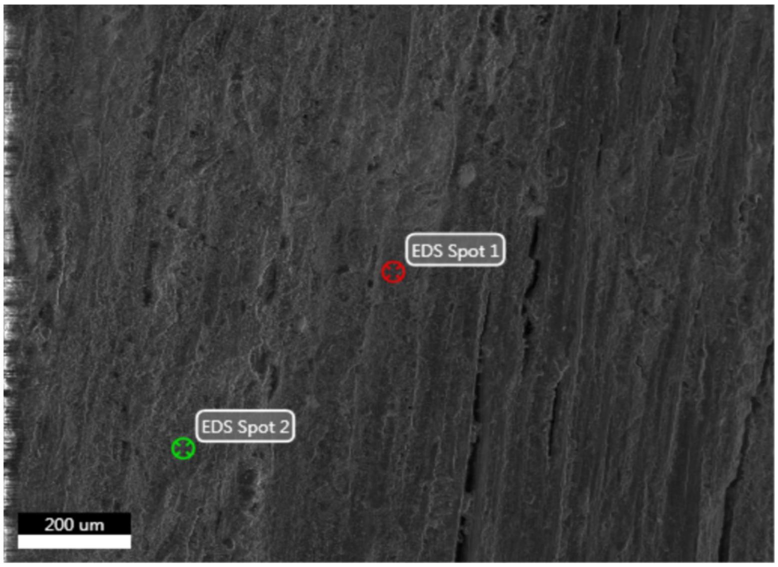
SEM-EDS analysis for translucent white finish on plywood ceilings and soffits

Matero

Author: prnuser
Creation: 12/21/2016

Sample Name: P1

Area 1

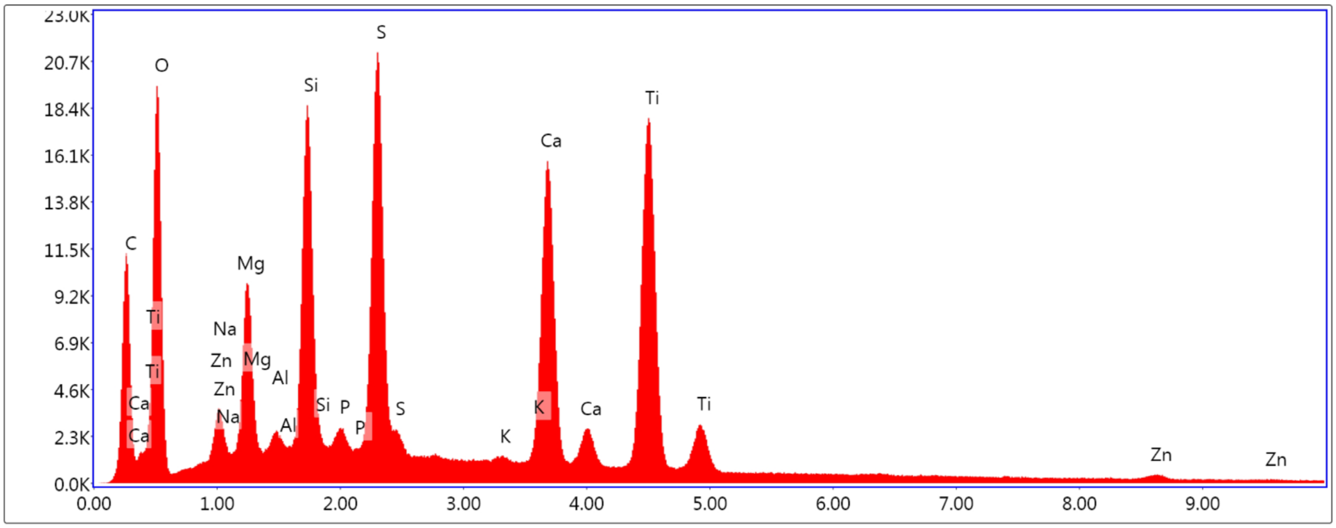


Notes:

EDS Spot 1

kV: 15 Mag: 200 Takeoff: 36 Live Time(s): 30 Amp Time(µs): 1.92 Resolution:(eV)134.

EDS Spot 1



Lsec: 30.0 0 Cnts 0.000 keV Det: Octane Super Det

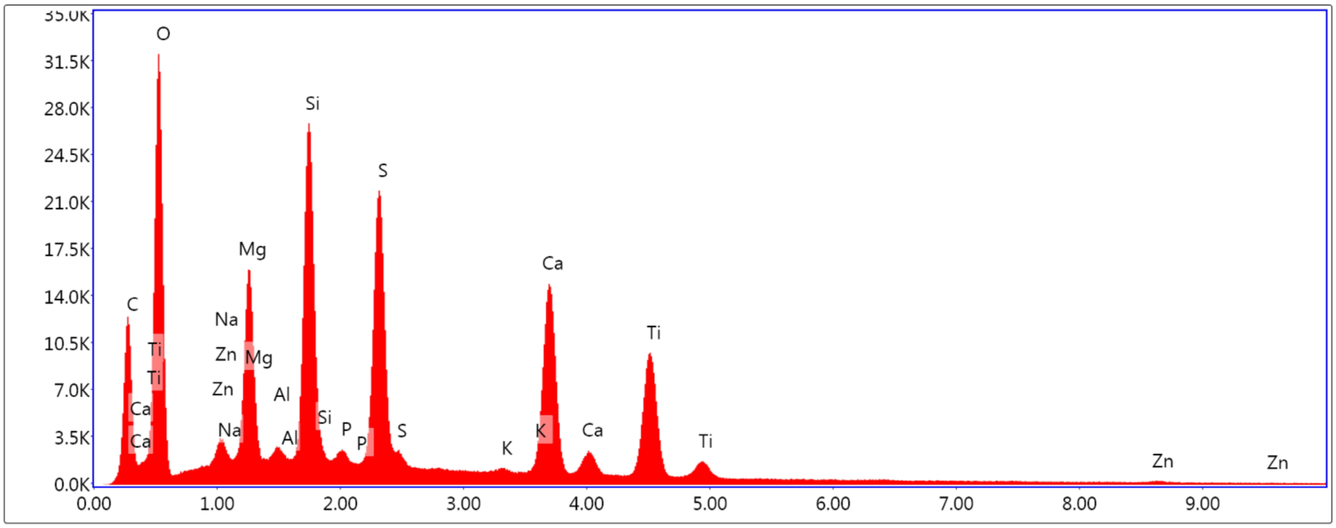
eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	R	A	F
C K	16.57	28.87	1405.44	9.44	0.0458 0.0458	1.1305	0.9381	0.2444	1.0000
O K	33.16	43.38	4902.29	9.68	0.0654 0.0654	1.0784	0.9604	0.1828	1.0000
NaK	0.00	0.00	0.04	99.99	0.0000 0.0000	0.9757	0.9870	0.4499	1.0035
MgK	2.95	2.54	2422.41	5.76	0.0177 0.0177	0.9914	0.9947	0.6022	1.0056
AlK	0.31	0.24	291.00	7.69	0.0022 0.0022	0.9537	1.0018	0.7137	1.0099
SiK	5.41	4.03	5489.36	3.56	0.0434 0.0434	0.9737	1.0085	0.8139	1.0126
P K	0.67	0.45	548.03	4.89	0.0054 0.0054	0.9344	1.0148	0.8524	1.0207
S K	8.22	5.37	6988.38	2.69	0.0722 0.0722	0.9519	1.0207	0.9046	1.0200
K K	0.26	0.14	169.40	14.45	0.0025 0.0025	0.8987	1.0360	0.9642	1.0741
CaK	11.51	6.01	6024.29	2.34	0.1086 0.1086	0.9142	1.0402	0.9794	1.0534
TiK	19.34	8.45	7498.09	2.33	0.1595 0.1595	0.8268	1.0473	0.9763	1.0214
ZnK	1.61	0.51	112.04	18.20	0.0137 0.0137	0.7596	1.0410	0.9990	1.1255

EDS Spot 2

kV: 15 Mag: 200 Takeoff: 36 Live Time(s): 30 Amp Time(µs): 1.92 Resolution:(eV)134.

EDS Spot 2



Lsec: 30.0 0 Cnts 0.000 keV Det: Octane Super Det

eZAF Smart Quant Results

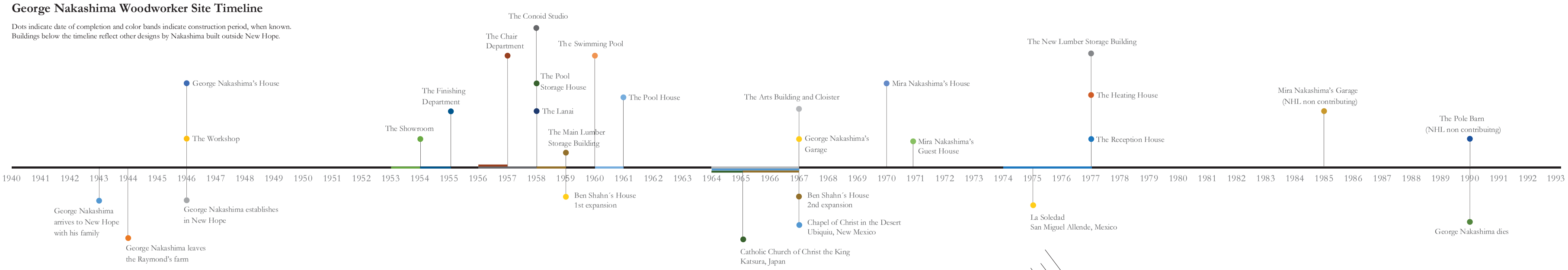
Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	R	A	F
C K	18.04	28.81	1583.36	9.47	0.0463 0.0463	1.1042	0.9504	0.2323	1.0000
O K	39.93	47.89	7925.76	9.15	0.0948 0.0948	1.0524	0.9719	0.2255	1.0000
NaK	0.01	0.01	5.86	17.40	0.0000 0.0000	0.9515	0.9975	0.4758	1.0040
MgK	4.60	3.63	4322.34	5.30	0.0283 0.0283	0.9665	1.0048	0.6336	1.0059
AlK	0.41	0.29	421.16	6.29	0.0028 0.0028	0.9296	1.0116	0.7279	1.0106
SiK	7.35	5.02	8215.50	3.34	0.0583 0.0583	0.9489	1.0180	0.8252	1.0115
P K	0.58	0.36	513.27	4.92	0.0046 0.0046	0.9104	1.0239	0.8492	1.0188
S K	8.00	4.78	7340.95	2.67	0.0680 0.0680	0.9273	1.0295	0.9025	1.0168
K K	0.33	0.16	224.18	9.29	0.0029 0.0029	0.8751	1.0437	0.9647	1.0607
CaK	10.37	4.96	5799.40	2.26	0.0938 0.0938	0.8901	1.0476	0.9798	1.0368
TiK	9.61	3.85	4070.04	2.45	0.0777 0.0777	0.8047	1.0540	0.9790	1.0256
ZnK	0.77	0.23	60.21	20.71	0.0066 0.0066	0.7377	1.0439	1.0022	1.1573

Appendix G

Drawing Sheets

George Nakashima Woodworker Site Timeline

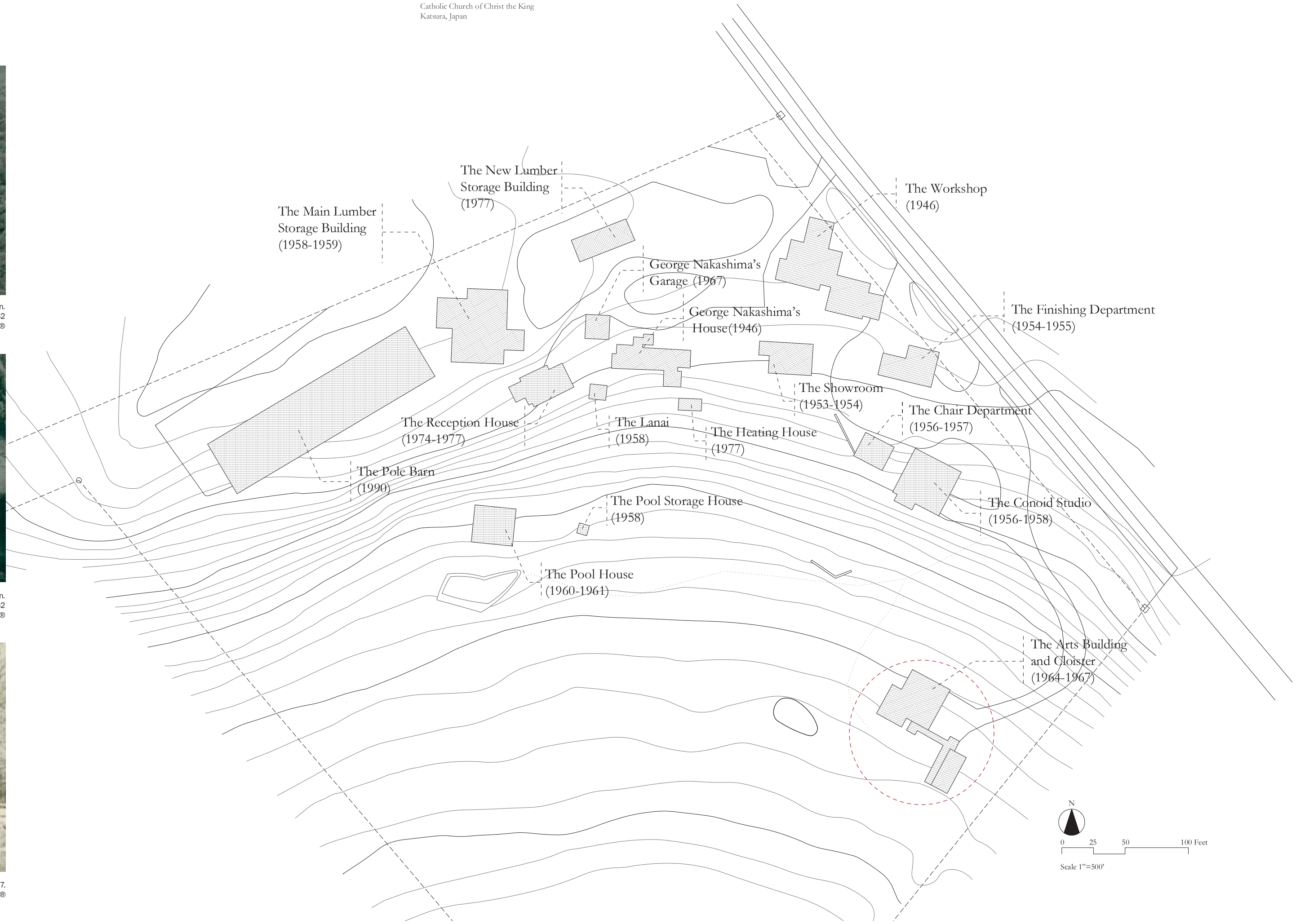
Dots indicate date of completion and color bands indicate construction period, when known.
Buildings below the timeline reflect other designs by Nakashima built outside New Hope.



Aerial view of the property prior to the Arts Building construction.
Looking northward. Ca. 1962
Courtesy of Ezra Stoller/Esto®

Aerival view prior to the Arts Building construction.
Looking eastward. Ca. 1962
Courtesy of Ezra Stoller/Esto®

West elevation. George Nakashima in front of the Arts Building. 1967.
Courtesy of Ezra Stoller/Esto®



THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

THE ARCHITECTURAL CONSERVATION LABORATORY
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

Delineators:
Cesar Bargues Ballester

Survey Date:
Based on site plan dated June 4, 1990

SHEET DESCRIPTION
SITE PLAN OF
GEORGE NAKASHIMA WOODWORKER

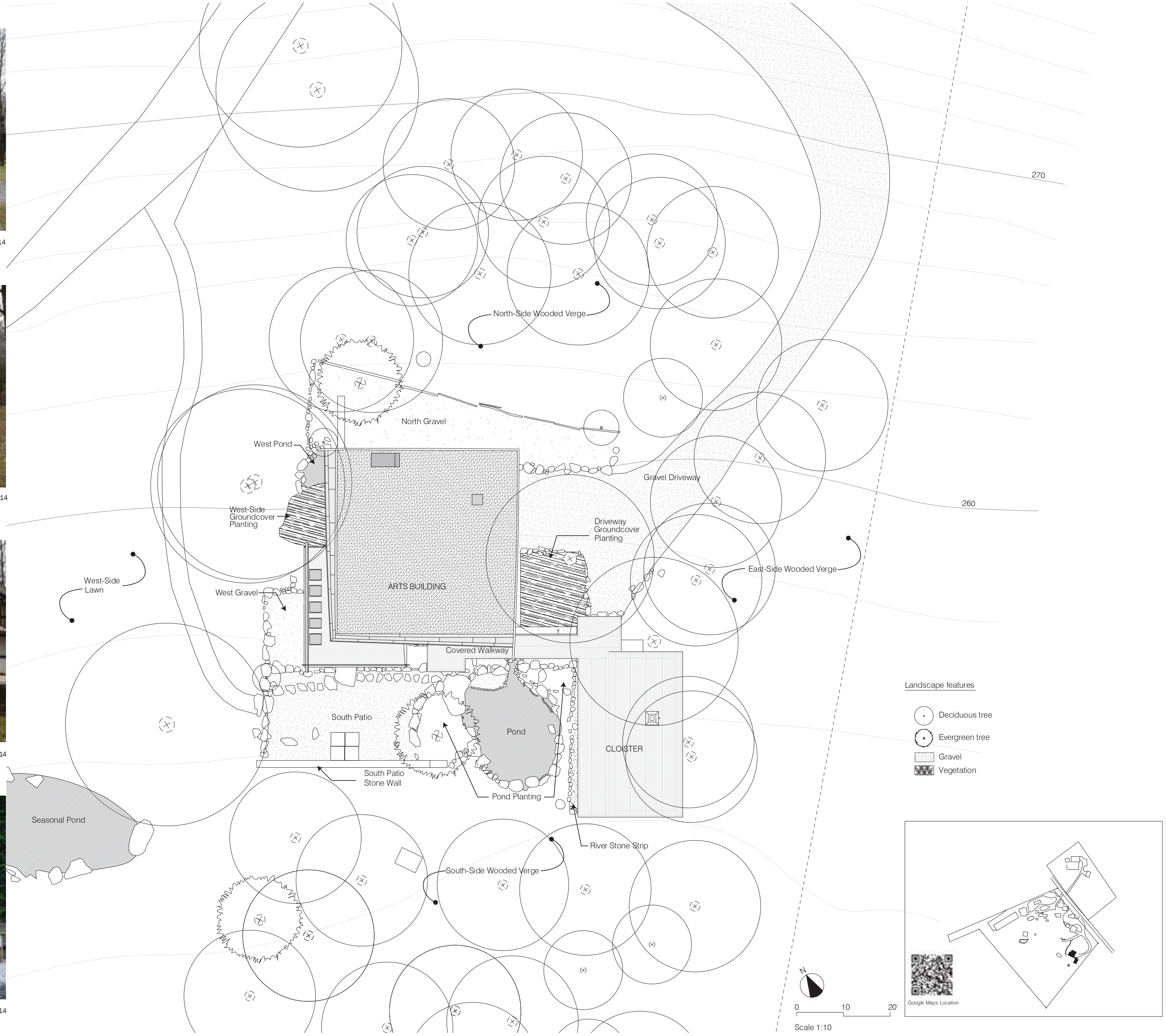
SHEET IDENTIFICATION
NAKA - A.01

Rear view from pathway approaching the Arts Building . December 2014

Rear view from road approaching the Arts Building. December 2014

The Arts Building and the Studio in the background. December 2014

South Patio in front of the Arts Building. September 2014



THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

THE ARCHITECTURAL CONSERVATION LABORATORY
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN · UNIVERSITY OF PENNSYLVANIA

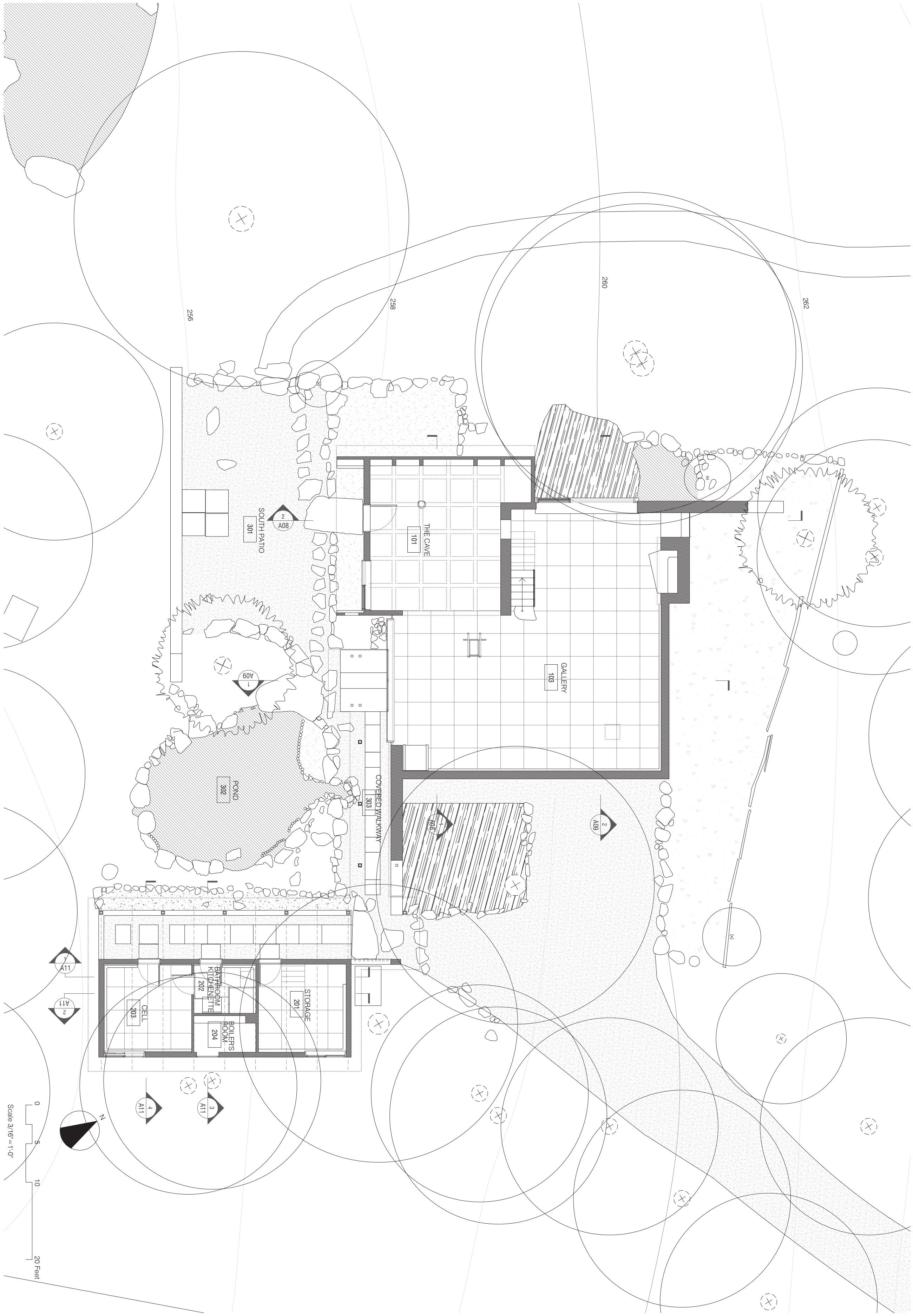
Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

Delineators:
Nicholas Pevzner - Landscape Architect
Cesar Bargues Ballester

Survey Date:
Nicholas Pevzner, Jan. 2016

SHEET DESCRIPTION
THE ARTS BUILDING AND CLOISTER
SITE PLAN

SHEET IDENTIFICATION
NAKA - A.02



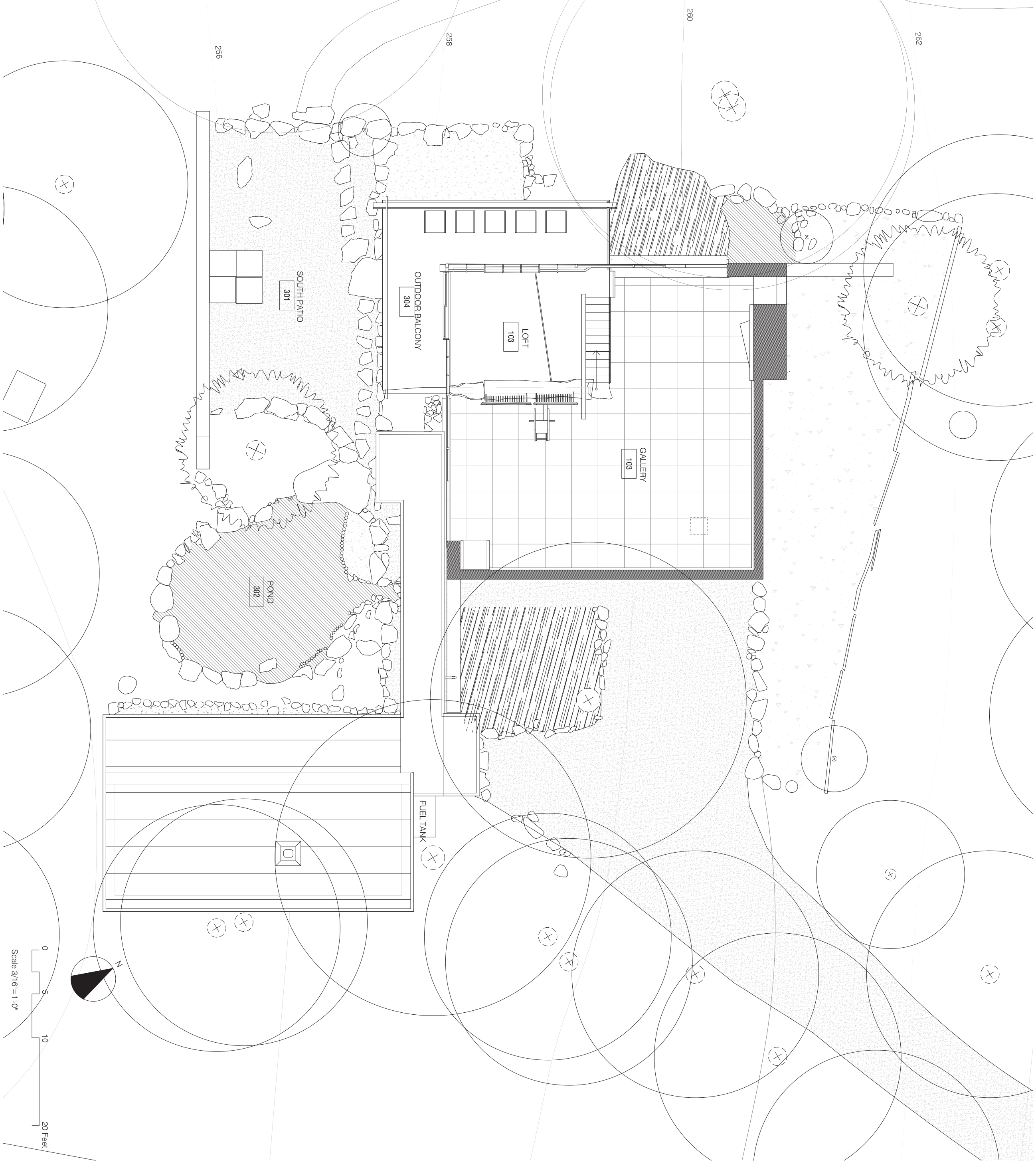
THE ARTS BUILDING AND CLOISTER George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania				SHEET IDENTIFICATION NAKA - A.03
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Nicholas Pevzner - Landscape Architect Cesar Bargues Ballester	Survey Date: Building, Sept. - Dec. 2014 Landscape, Jan. 2016	SHEET DESCRIPTION GROUND FLOOR

Building Detail. October 2015

View from the Arts Building balcony towards the Cloister. October 2015

View of the covered walkway towards the Arts Building platform. November 2015

View of the balcony and access from the mezzanine. November 2015



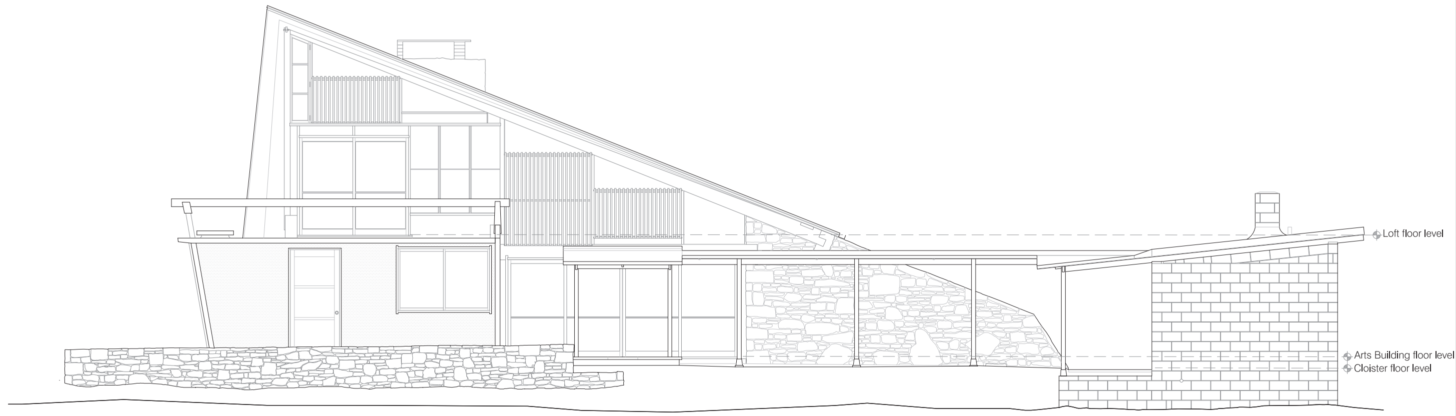
THE ARTS BUILDING AND CLOISTER George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania				SHEET IDENTIFICATION NAKA - A.04
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Cesar Bargues Ballester	Survey Date: September- December 2014	SHEET DESCRIPTION FIRST FLOOR

Exterior view of the Arts Building from the Cloister. December 2014

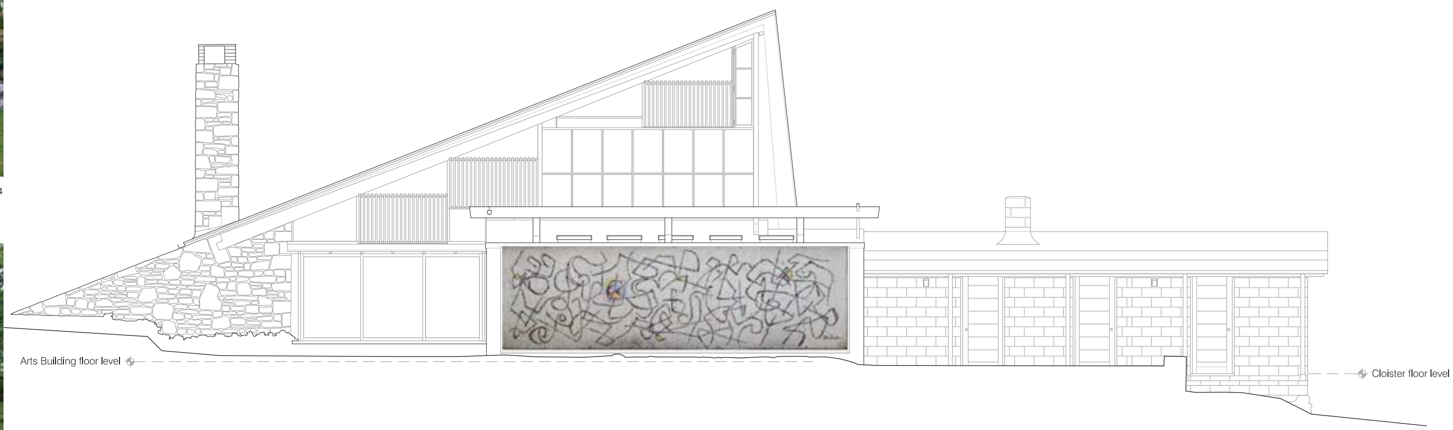
View of the Arts Building and Cloister from southwest. December 2014

Exterior view of the Arts Building from the northwest. December 2014

Exterior view of the Arts Building from the southwest. December 2014



South Elevation
Scale 1/4" = 1 foot



West Elevation
Scale 1/4" = 1 foot

THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

THE ARCHITECTURAL CONSERVATION LABORATORY
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

Delineators: Cesar Bargues Ballester

Survey Date: September- December 2014

SHEET IDENTIFICATION
NAKA - A.05

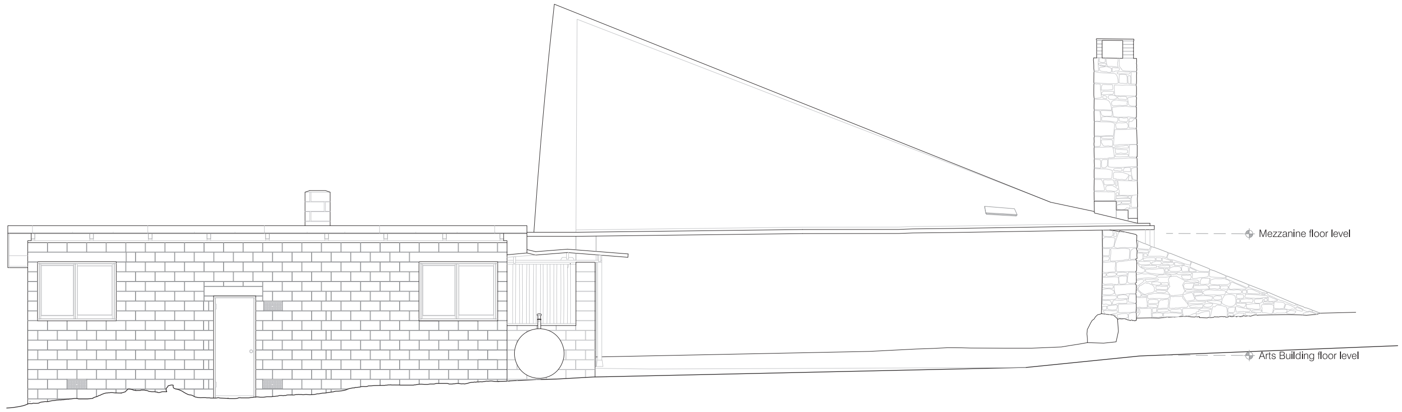
SHEET DESCRIPTION
SOUTHWEST AND NORTHWEST ELEVATIONS

Exterior view of the Arts Building from the northeast. September 2014

View of the Cloister from northeast. December 2014

Exterior view of the Arts Building from the northeast. October 2014

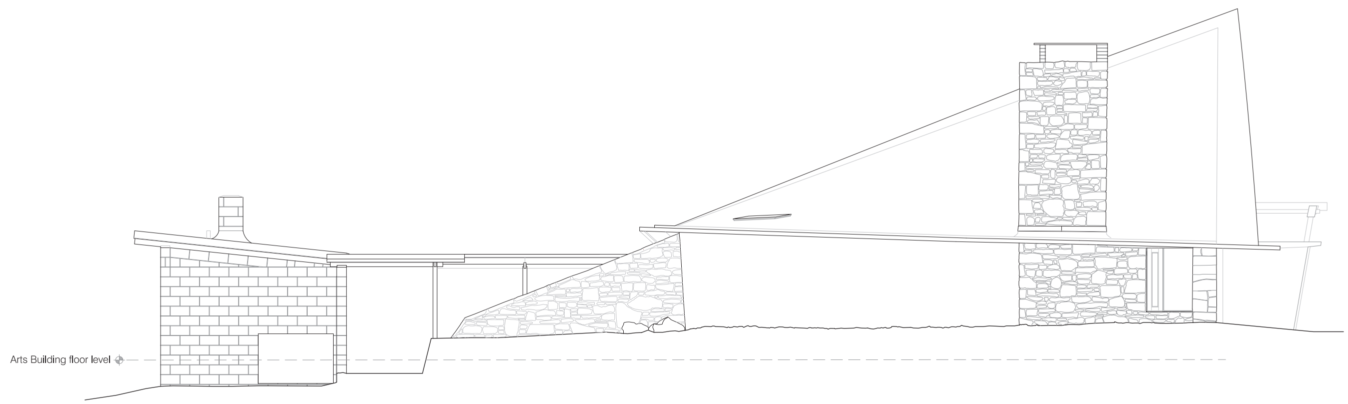
The Cloister and the connection to the Arts Building. January 2015



0 1 3 6 12 Feet

East Elevation

Scale 1/4" = 1 foot



0 1 3 6 12 Feet

North Elevation

Scale 1/4" = 1 foot

THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

THE ARCHITECTURAL CONSERVATION LABORATORY
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA

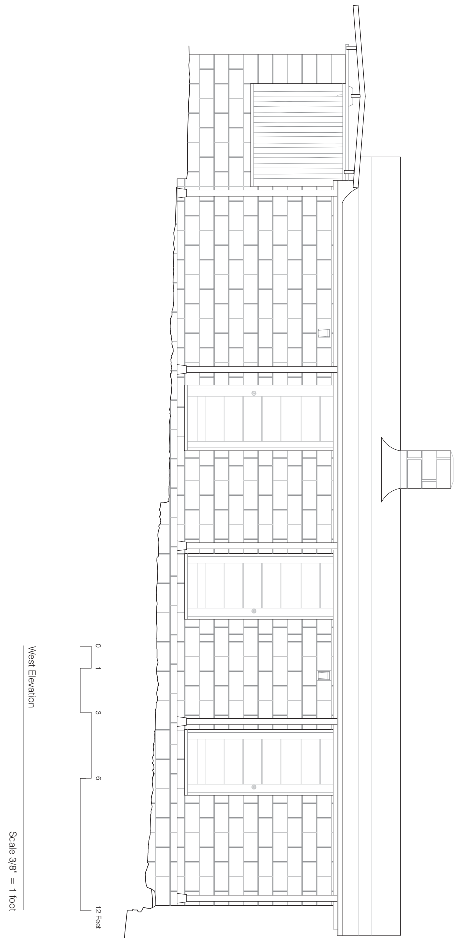
Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

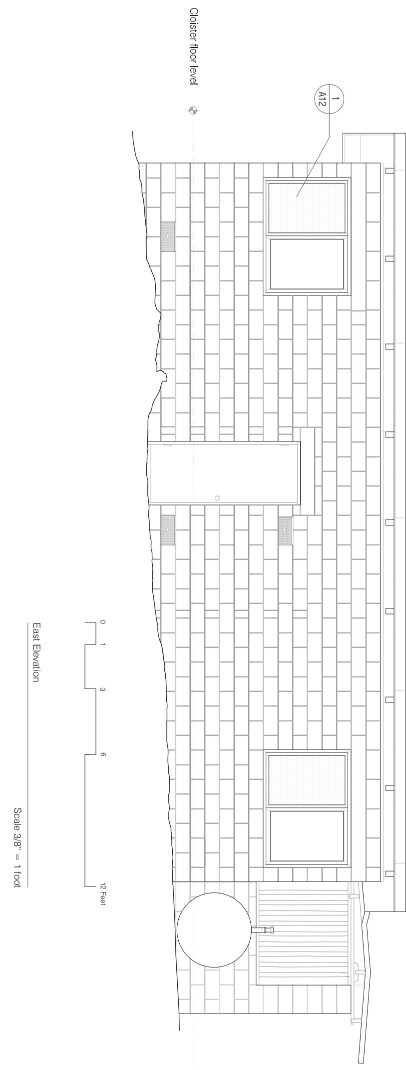
Delineators: Cesar Bargues Ballester

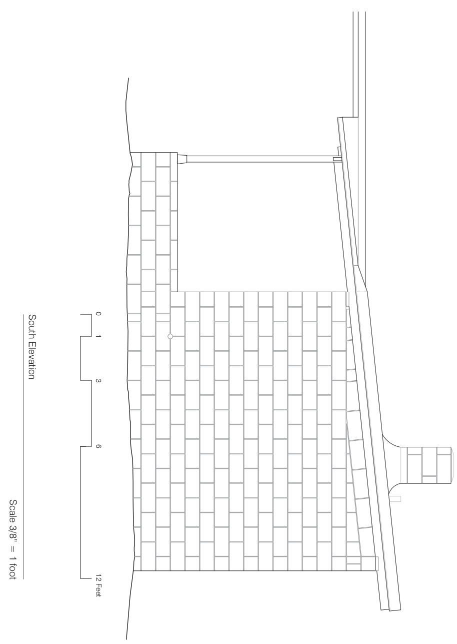
Survey Date: September- December 2014

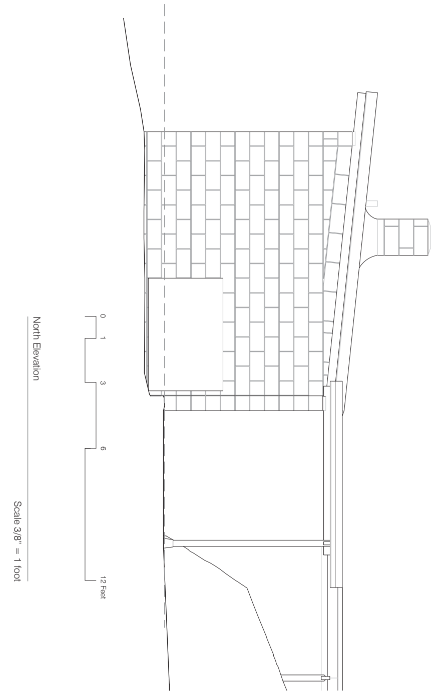
SHEET IDENTIFICATION: NAKA - A.06

SHEET DESCRIPTION: SOUTHEAST AND NORTHEAST ELEVATIONS









THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

SHEET IDENTIFICATION

NAKA - A.07

THE ARCHITECTURAL CONSERVATION LABORATORY

GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA

Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

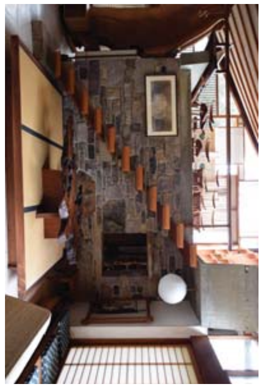
Delineators:
Cesar Bargues Ballester

Survey Date:
September- December 2014

SHEET DESCRIPTION

THE CLOISTER: ELEVATIONS

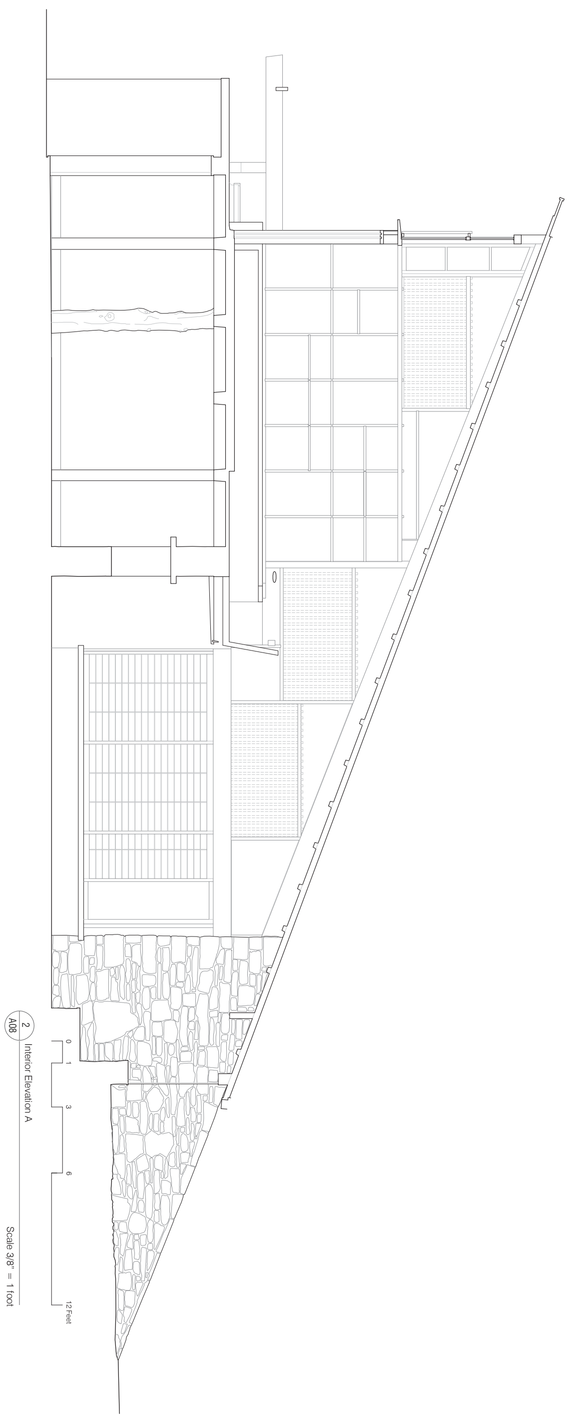
Interior view of the Cave. October 2014

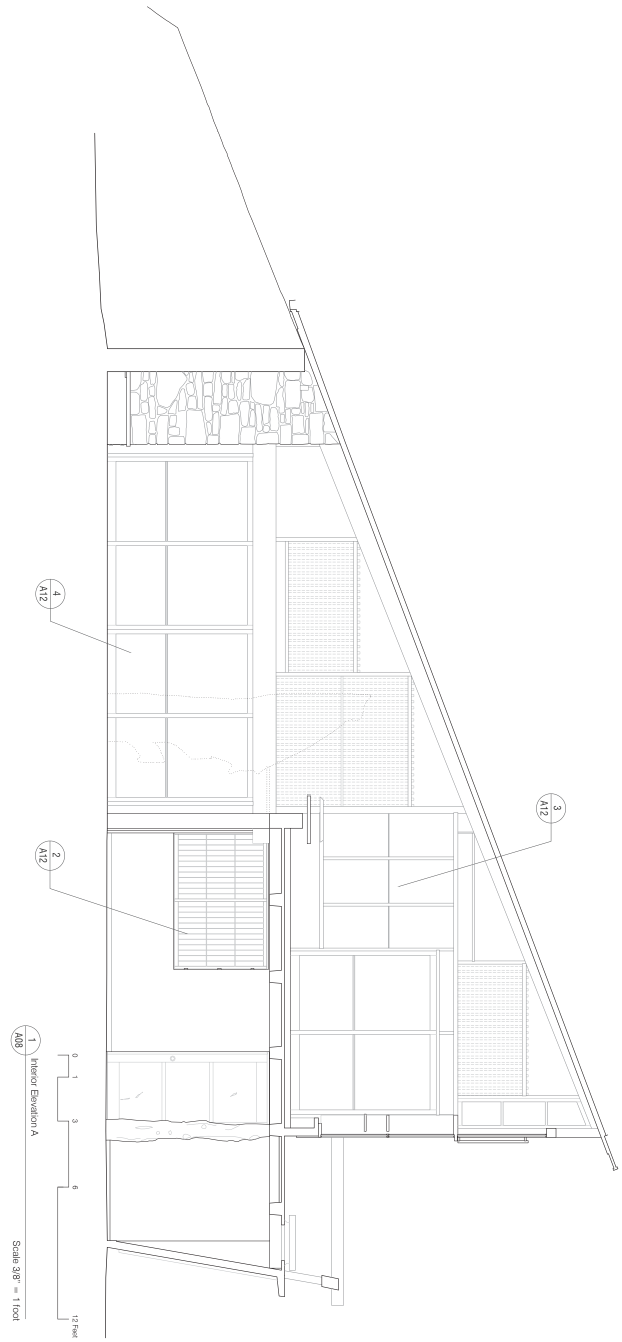


Cantilevered stairs and the Loft. September 2014

View towards the Cave and the Loft. May 2015

Interior view towards the south. May 2015





THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

SHEET IDENTIFICATION

NAKA - A.08

THE ARCHITECTURAL CONSERVATION LABORATORY

GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA

Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

Delineators:
Cesar Bargues Ballester

Survey Date:
September- December 2014

SHEET DESCRIPTION

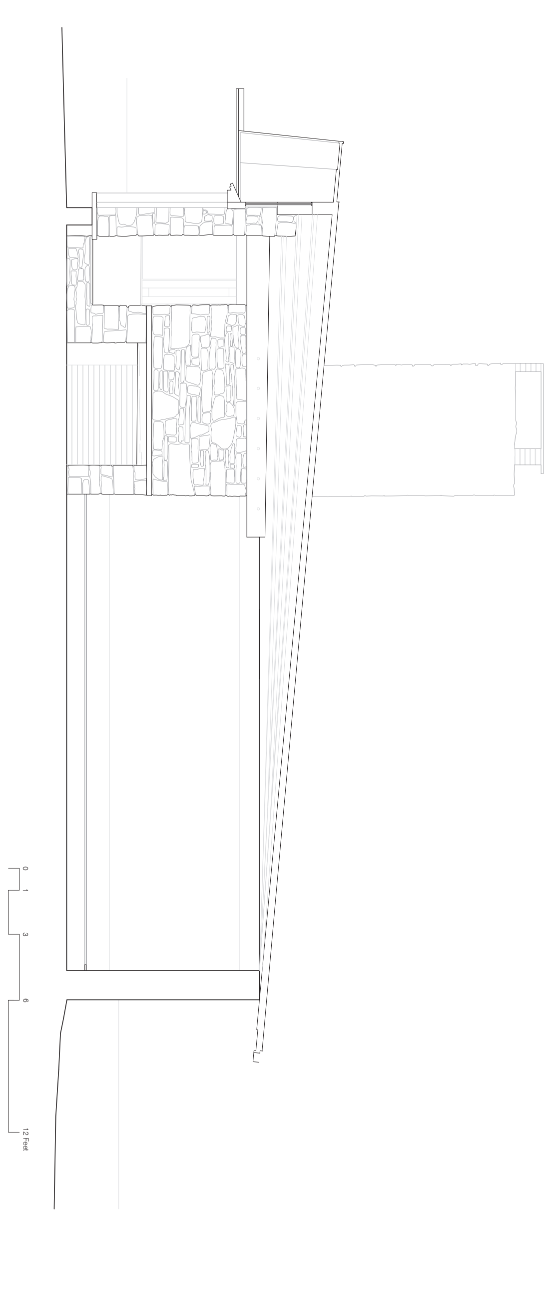
THE ARTS BUILDING: INTERIOR ELEVATIONS


Interior view of the Arts Building along east wall. September 2014

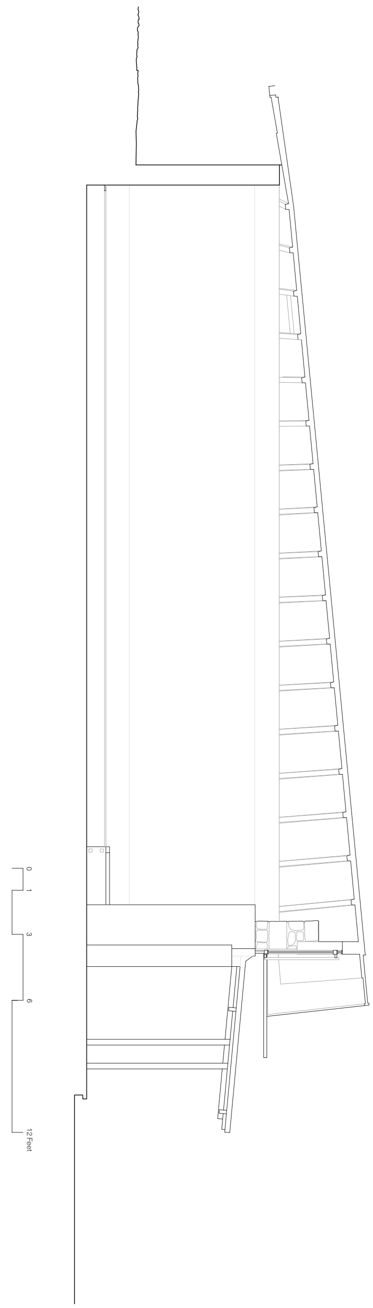

Interior view of the Arts Building. September 2014


View of the fireplace area. October 2014


Interior view of the Arts Building. November 2014



2
A09
Interior Elevation C
Scale 3/8" = 1 foot



1
A09
Interior Elevation B
Scale 3/8" = 1 foot

THE ARTS BUILDING AND CLOISTER

George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania

THE ARCHITECTURAL CONSERVATION LABORATORY
GRADUATE PROGRAM IN HISTORIC PRESERVATION
SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA

Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

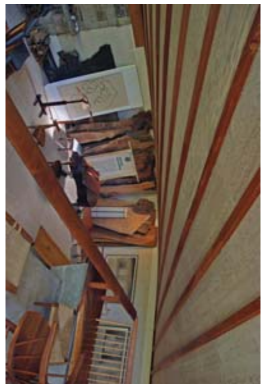
Delineators: Cesar Bargues Ballester

Survey Date: September- December 2014

SHEET IDENTIFICATION
NAKA - A.09

SHEET DESCRIPTION
THE ARTS BUILDING: INTERIOR ELEVATIONS

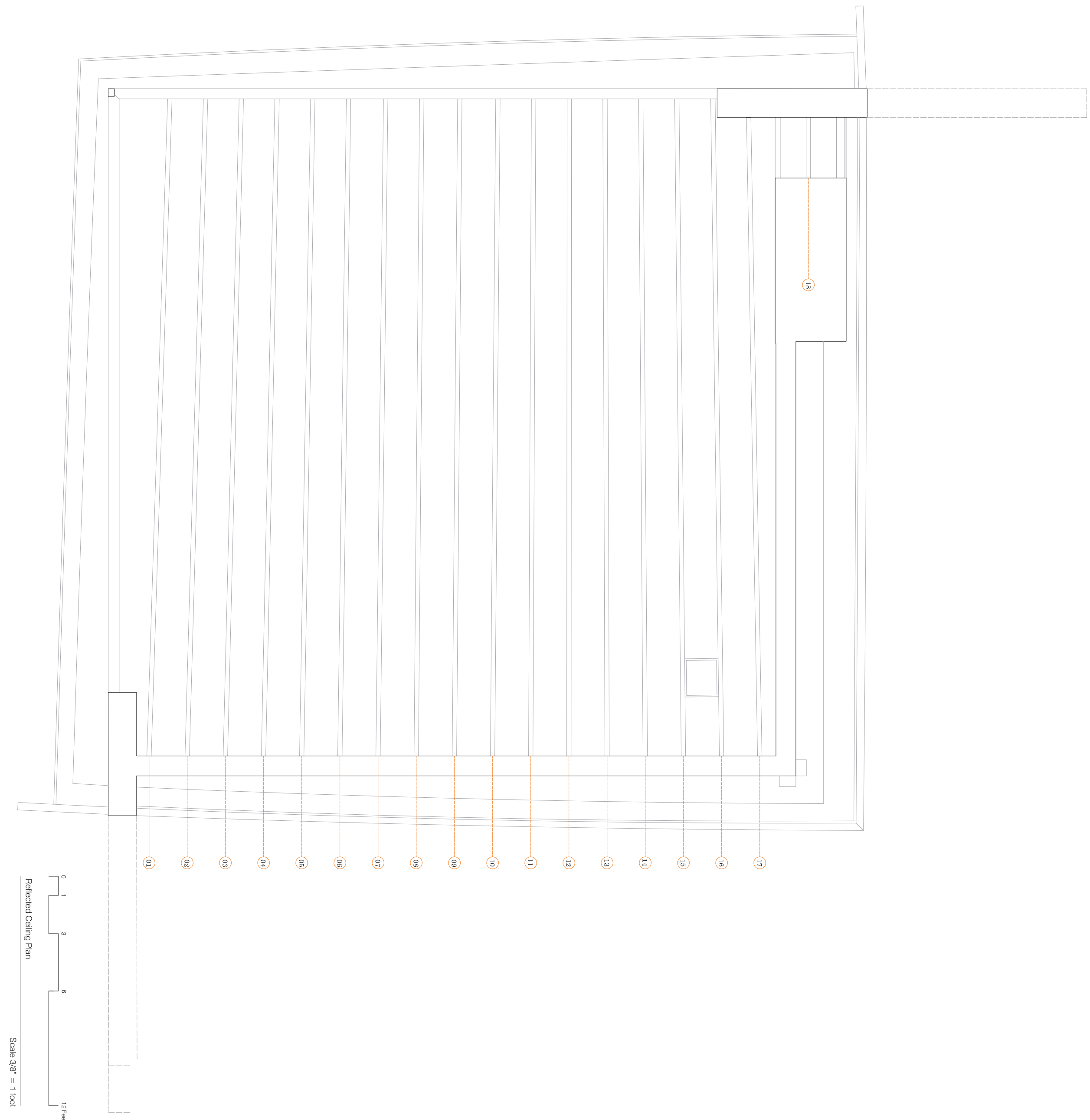
Exterior view of the Arts Building from the southwest, December 2015



Exterior view of the Arts Building from the northwest, September 2014

Exterior view of the hyperbolic paraboloid roof upper corner, October 2014

Exterior view of the hyperbolic paraboloid roof upper corner, October 2014



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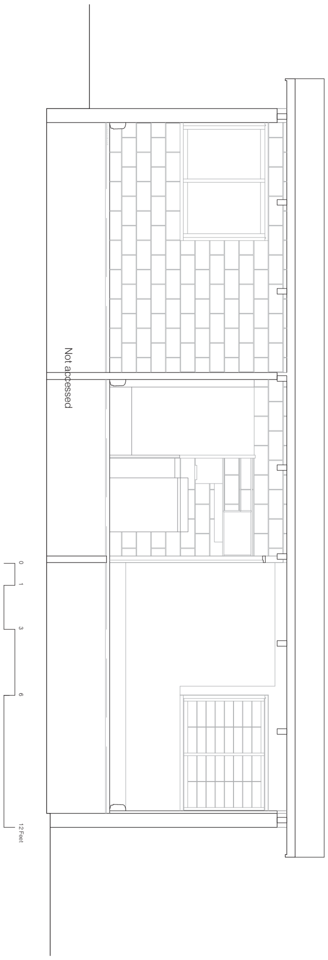
SHEET IDENTIFICATION

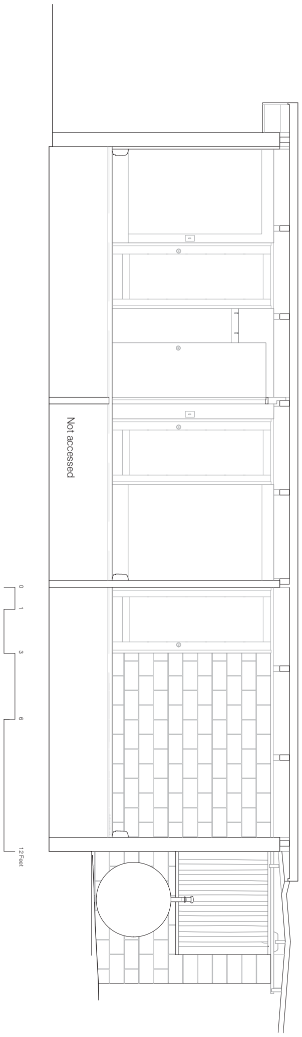
NAKA - A.10

SHEET DESCRIPTION

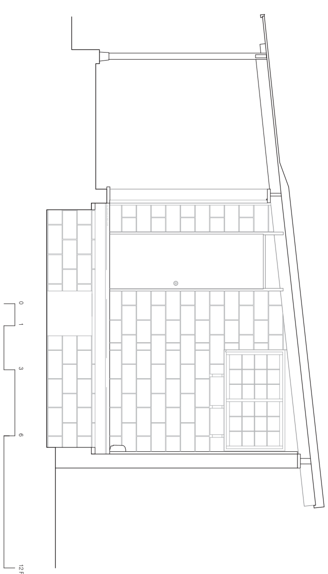
THE ARTS BUILDING:
REFLECTED CEILING PLAN



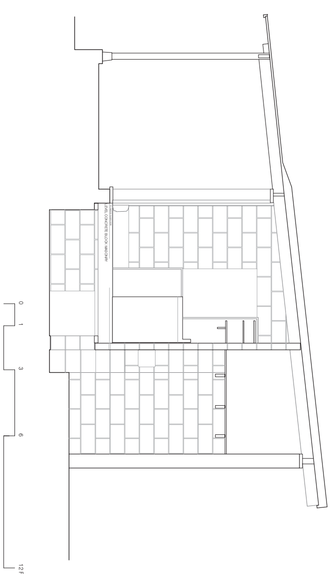
2
A11
Longitudinal Section I, Northeast Elevation
Scale 3/8" = 1 foot



1
A11
Longitudinal Section H, Northwest Elevation
Scale 3/8" = 1 foot



4
A11
Cross Section F, Through Cell
Scale 3/8" = 1 foot



3
A11
Cross Section G, Through Kitchenette
Scale 3/8" = 1 foot

THE ARTS BUILDING AND CLOISTER

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SHEET IDENTIFICATION

NAKA - A.11

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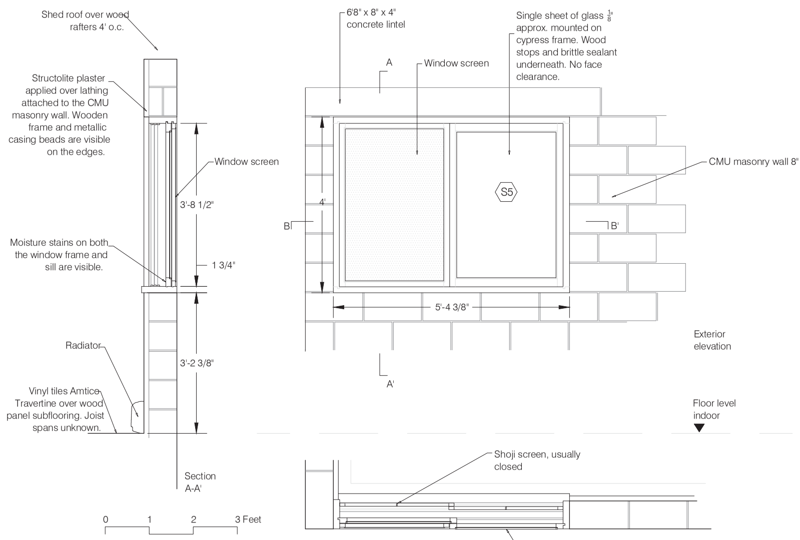
Delineators:
Cesar Bargues Ballester

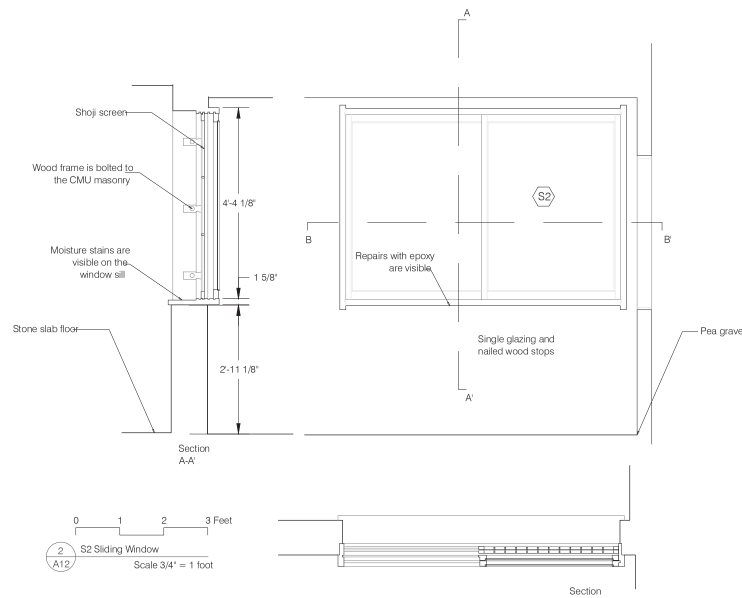
Survey Date:
September- December 2014

SHEET DESCRIPTION

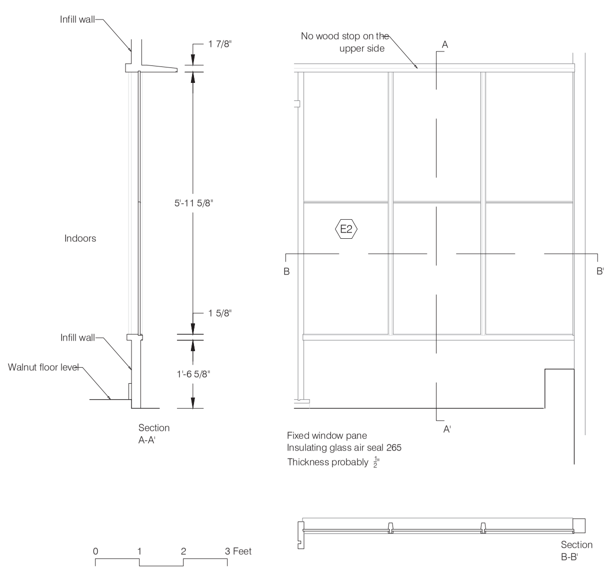
THE CLOISTER: SECTIONS



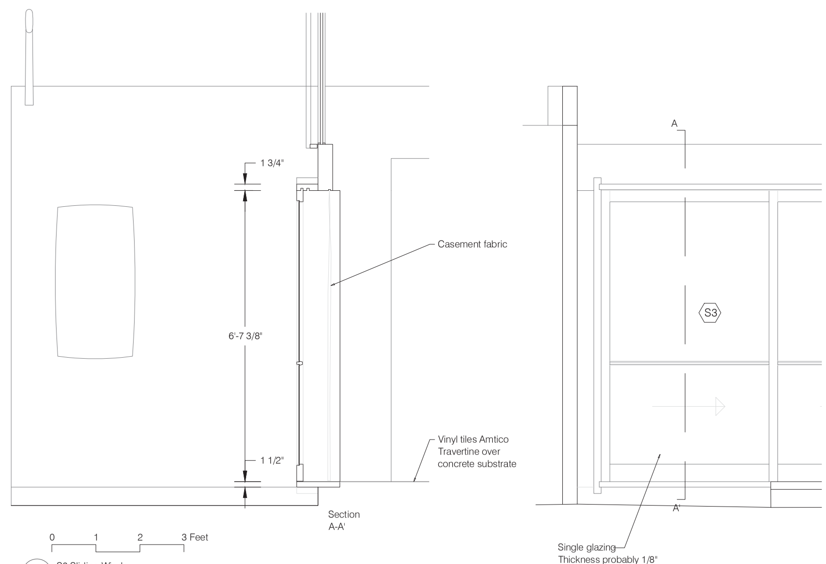
1 A12 S5 Window Type
Scale 3/4" = 1 foot



2 A12 S2 Sliding Window
Scale 3/4" = 1 foot



3 A12 E3 Window
Scale 3/4" = 1 foot



4 A12 S3 Sliding Window
Scale 3/4" = 1 foot

THE ARTS BUILDING AND CLOISTER

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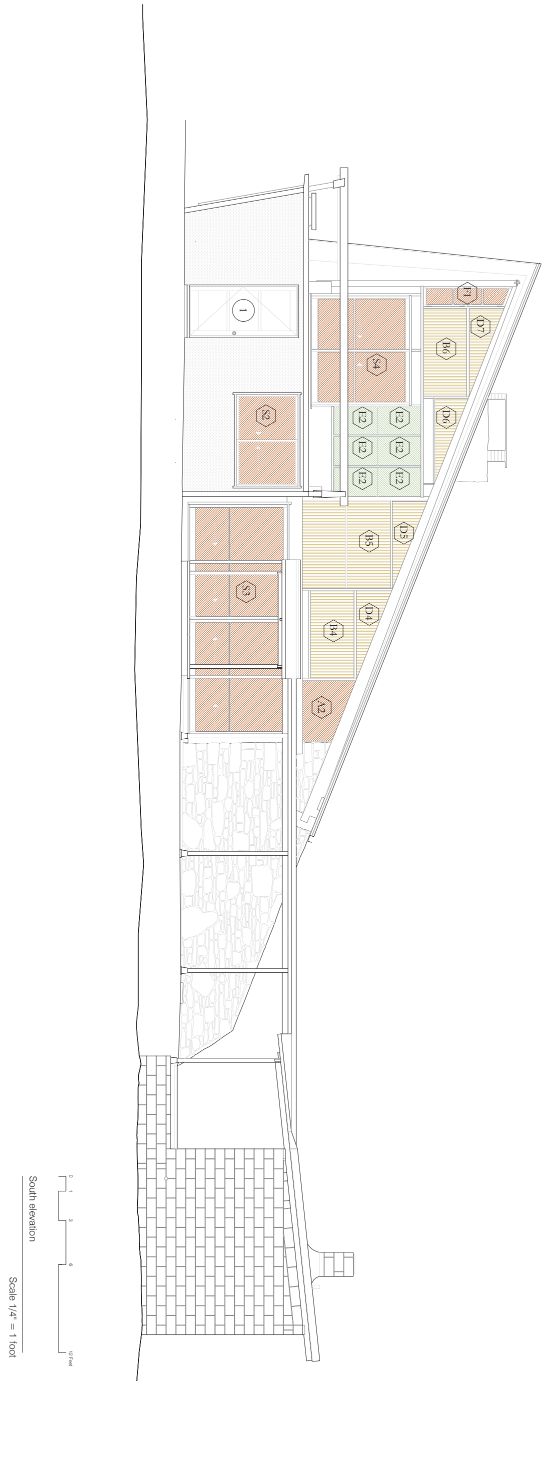
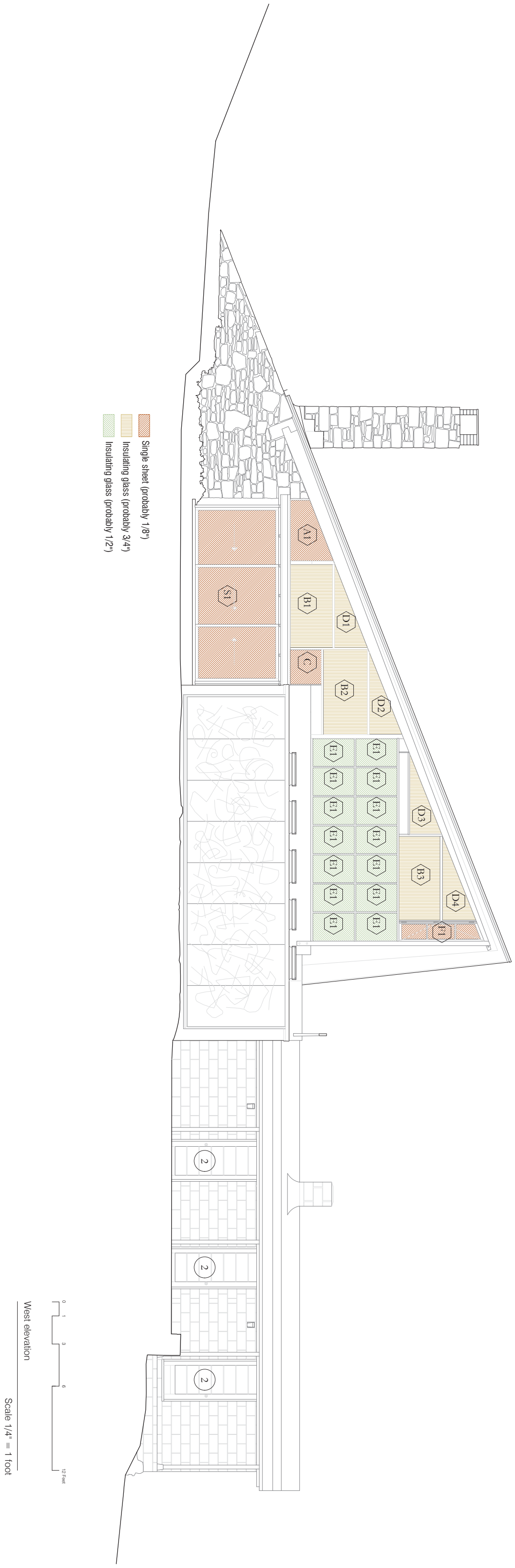
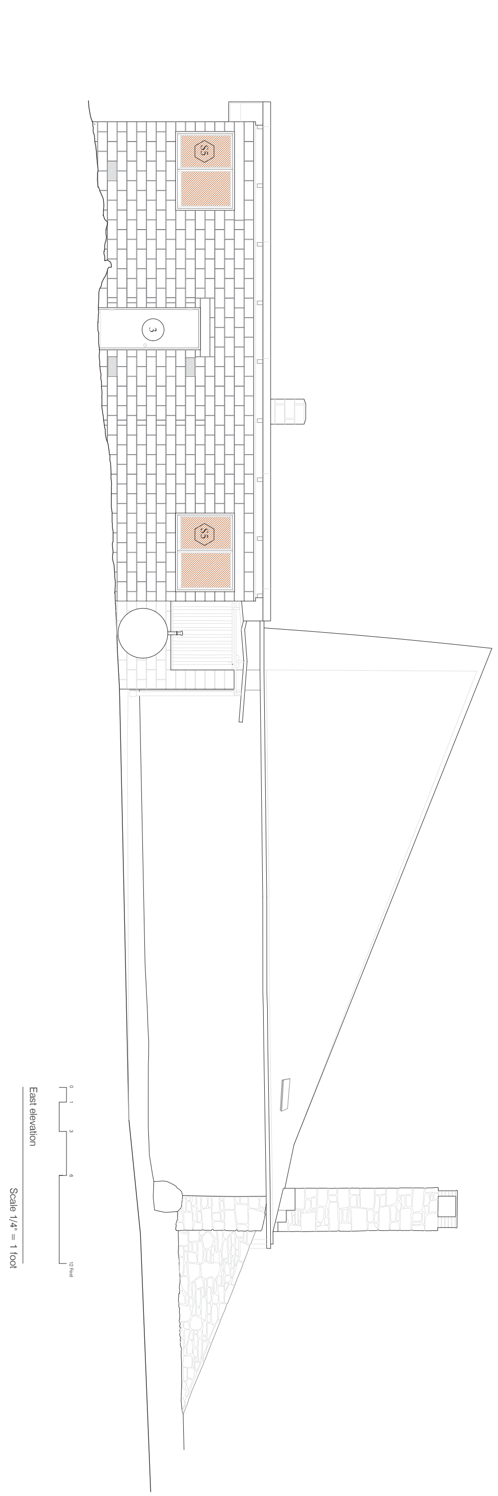
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVERSITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Cesar Bargues Ballester	Survey Date: September- December 2014

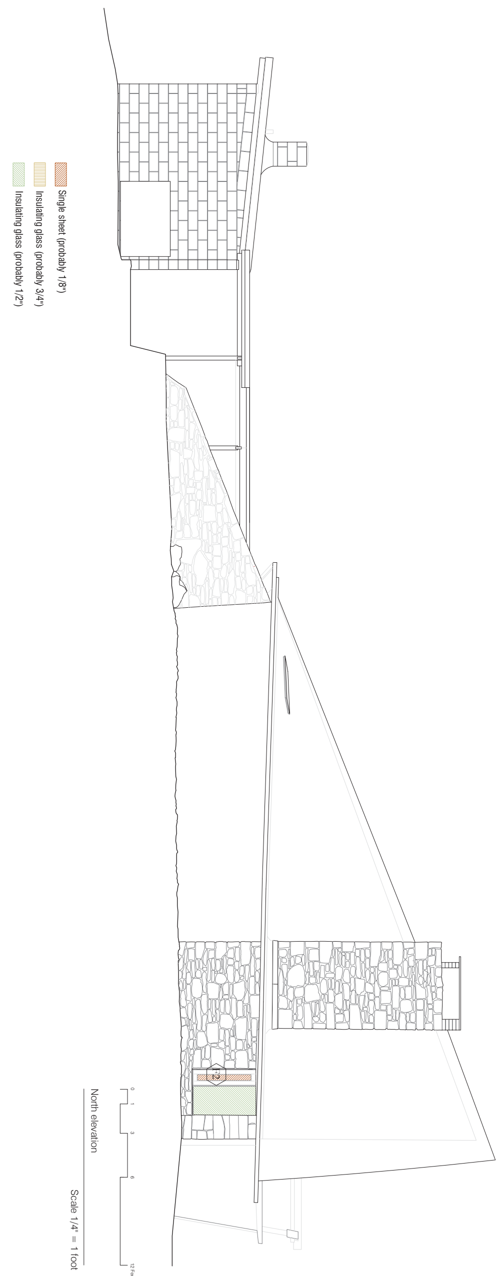
SHEET IDENTIFICATION
NAKA - A.12
SHEET DESCRIPTION
ARCHITECTURAL DETAILS





THE ARTS BUILDING AND CLOISTER George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania				SHEET IDENTIFICATION NAKA - A.13
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Cesar Bargues Ballester	Survey Date: September- December 2014	SHEET DESCRIPTION WINDOW SCHEDULE: SOUTHWEST AND NORTHWEST





THE ARTS BUILDING AND CLOISTER

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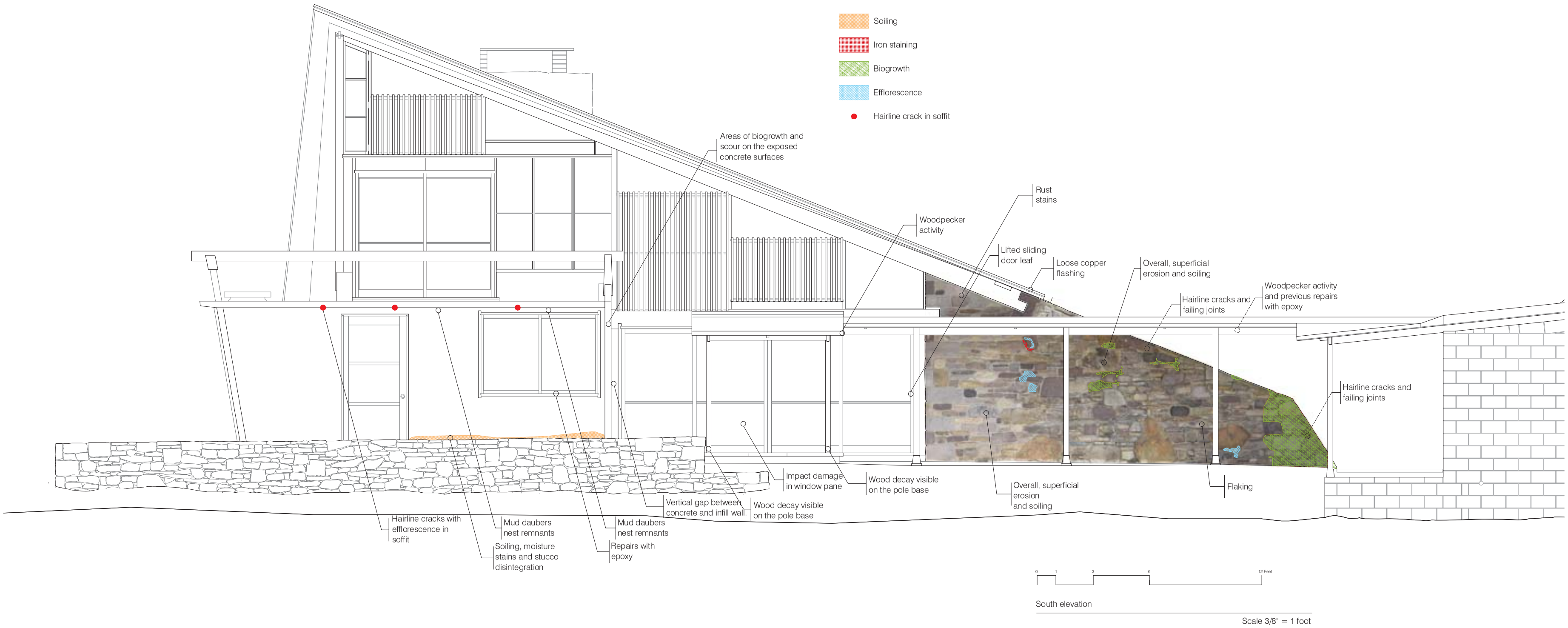
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Cesar Bargues Ballester	Survey Date: September- December 2014	SHEET IDENTIFICATION NAKA - A.14 SHEET DESCRIPTION WINDOW SCHEDULE: SOUTHEAST AND NORTHEAST



Rust stains.

Darkened finish on the wooden elements. Note damage by squirrels

Efflorescence visible on stone masonry

Biological colonization and superficial erosion on the concrete surface

THE ARTS BUILDING AND CLOISTER

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Frank Matero - Project Director
William Whitaker - Associate Director
John Hinchman - Heritage Surveyor
Cesar Bargues Ballester - Project Manager

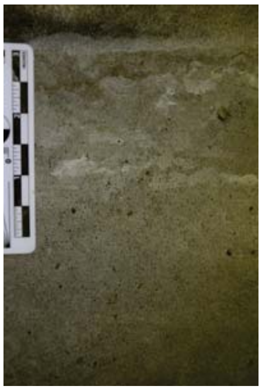
Delineators:
Cesar Bargues Ballester

Condition Survey Date:
March 2015

SHEET IDENTIFICATION
NAKA - C.01

SHEET DESCRIPTION
THE ARTS BUILDING: SOUTHWEST ELEVATION

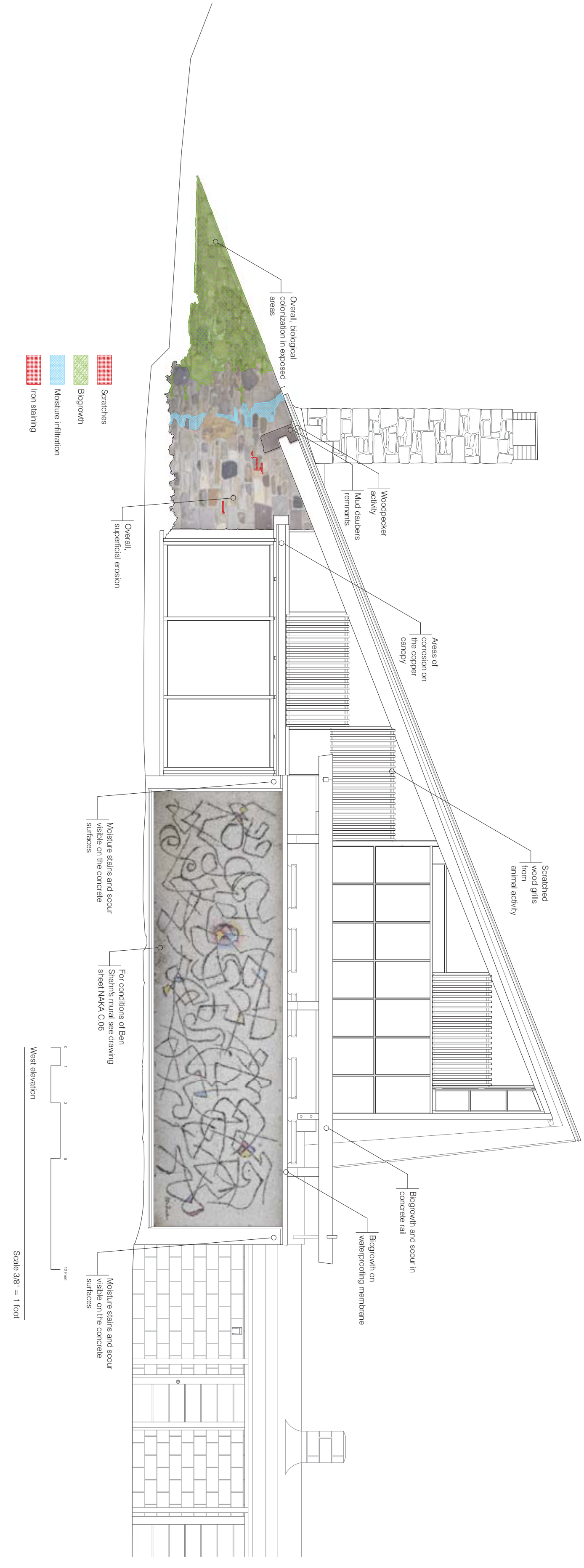
Biological colonization and moisture stains visible on the exposed concrete surface



Close-up view of moisture stains on the concrete surface

Close-up view of the cypress grills on the west elevation.
Note natural weathering and damage by squirrels

Biological colonization visible on the stone masonry



THE ARTS BUILDING AND CLOISTER

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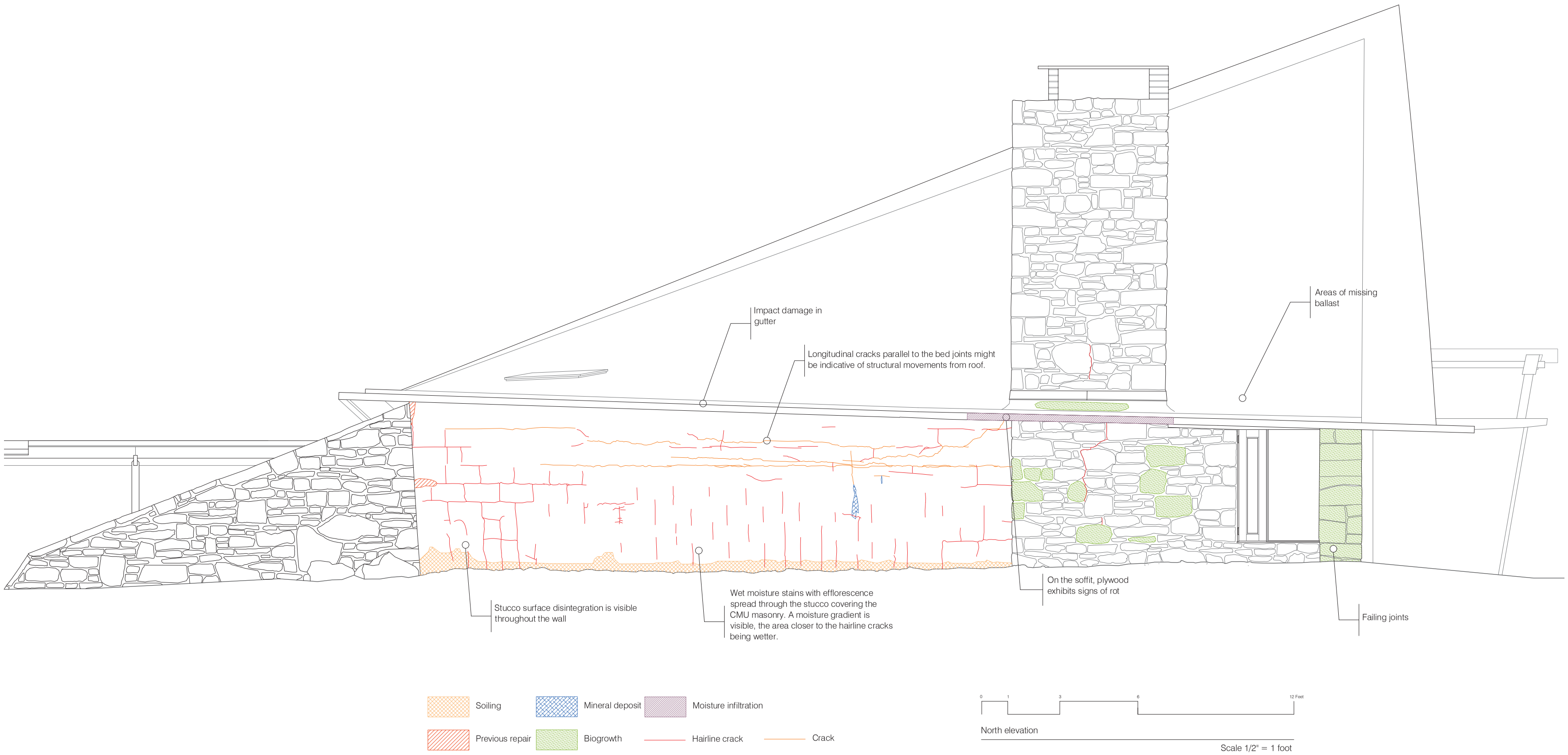
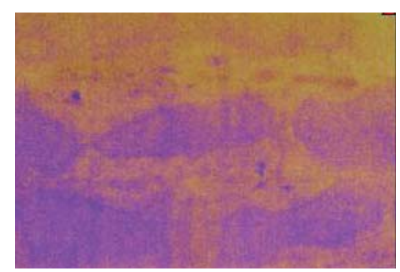


Hairline cracking and superficial erosion

Close-up view of the stucco disintegration

Darker wet areas and hairling cracking tipically reveal the Waylite block perimeter



Overlaid infrared image on the previous photograph. Note how the darker wet areas are warmer.

THE ARTS BUILDING AND CLOISTER

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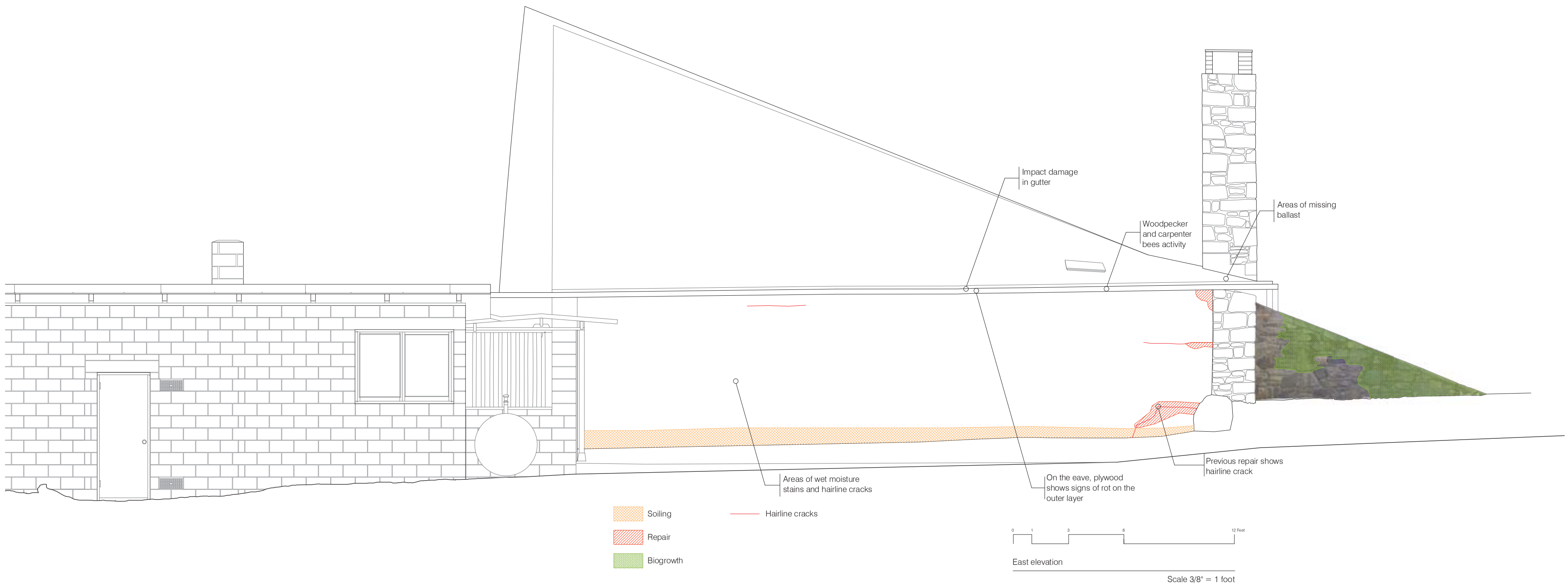
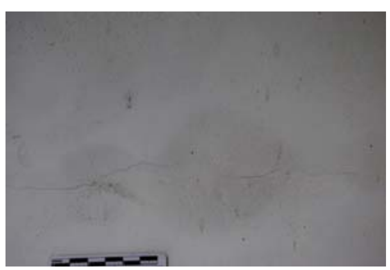
Survey Date: September- December 2014

SHEET DESCRIPTION: THE ARTS BUILDING: NORTHEAST ELEVATION

SHEET IDENTIFICATION: NAKA - C.03



Previous repair



Typical hairline crack along with dark wet areas

Typical rot visible on the plywood edge adjoining the fascia board

Typical woodpecker damage

THE ARTS BUILDING AND CLOISTER

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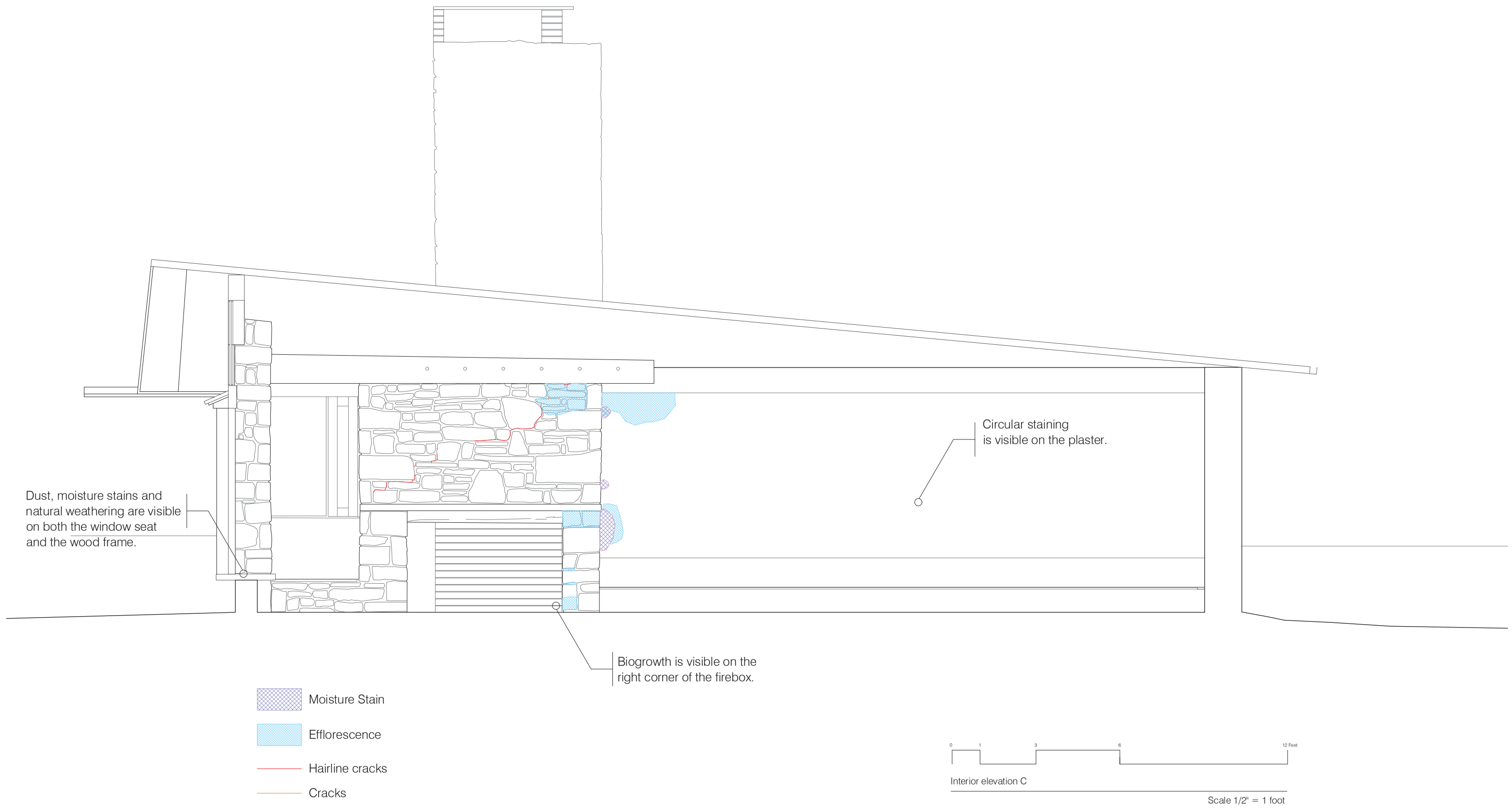
Cesar Bargues Ballester

Survey Date:
September- December 2014

SHEET IDENTIFICATION
NAKA - C.04

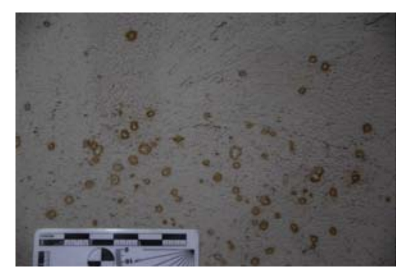
SHEET DESCRIPTION
THE ARTS BUILDING: SOUTHEAST ELEVATION




Cracking and efflorescence on the stone masonry


Moisture stains on the plaster and on the window seat


Scaling visible on the chimney hearth. Note minor damage by fire on the Amtico© Travertine flooring


Typical circular staining on the walls plastered with Structolite®

THE ARTS BUILDING AND CLOISTER

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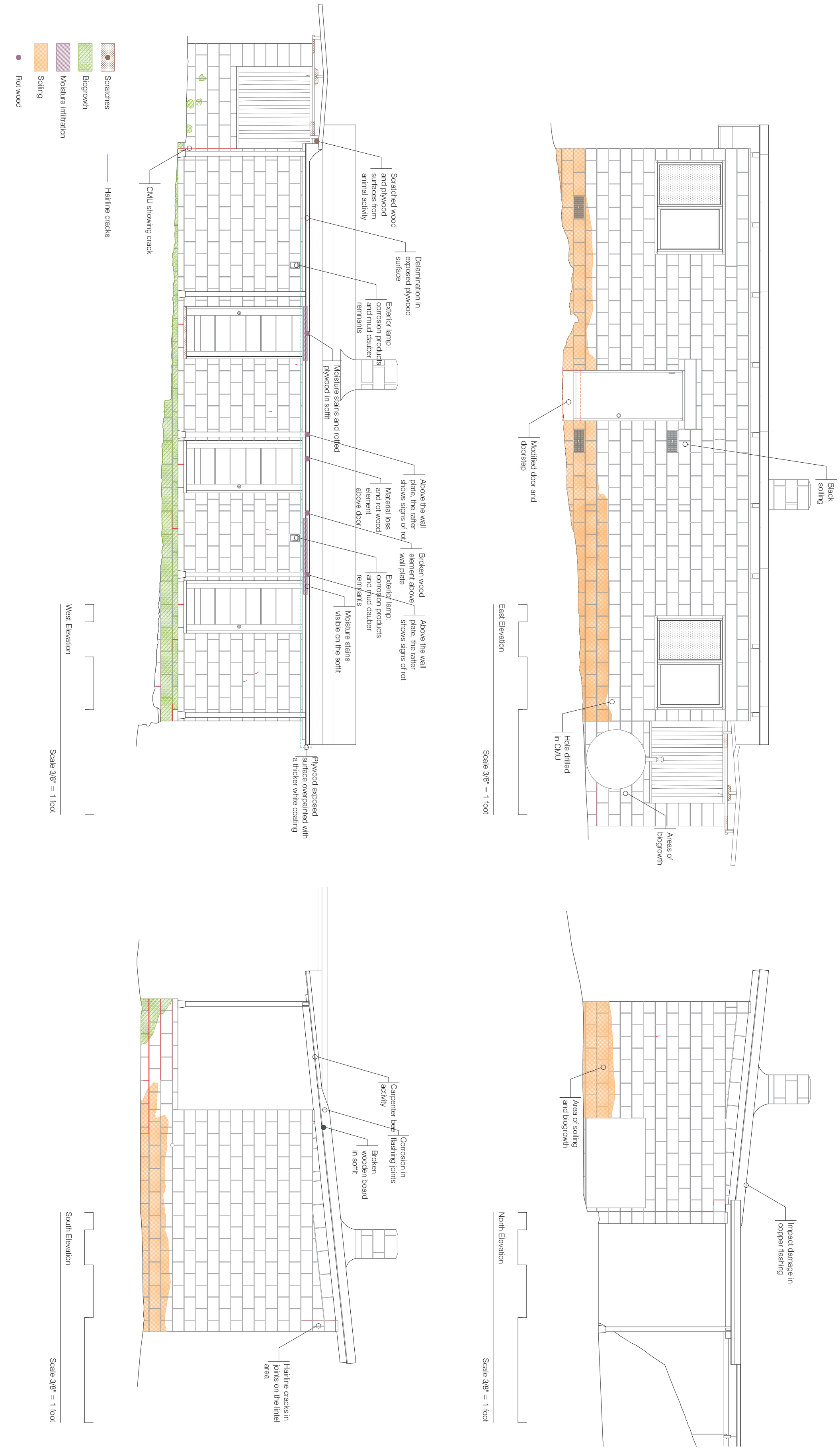
Delineators: Cesar Bargues Ballester

Survey Date: September- December 2014

SHEET IDENTIFICATION: NAKA - C.05

SHEET DESCRIPTION: THE ARTS BUILDING: INTERIORS



THE ARTS BUILDING AND CLOISTER George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania				SHEET IDENTIFICATION NAKA - C.06
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Cesar Bargues Ballester	Survey Date: September- December 2014	SHEET DESCRIPTION THE CLOISTER: ELEVATIONS

Missing tesserae

Color alteration

Granular disintegration

Biological colonization

Soiling

Missing tesserae

Color alteration

0 1 3 6

Ben Shahn's Mosaic

Scale 1" = 1 foot

THE ARTS BUILDING AND CLOISTER George Nakashima Foundation for Peace 1847 Aquetong Road New Hope, Pennsylvania				SHEET IDENTIFICATION NAKA - C.07
THE ARCHITECTURAL CONSERVATION LABORATORY GRADUATE PROGRAM IN HISTORIC PRESERVATION SCHOOL OF DESIGN - UNIVESRITY OF PENNSYLVANIA	Frank Matero - Project Director William Whitaker - Associate Director John Hinchman - Heritage Surveyor Cesar Bargues Ballester - Project Manager	Delineators: Cesar Bargues Ballester	Survey Date: September- December 2014	SHEET DESCRIPTION BEN SHAHN MOSAIC MURAL

Appendix H

Arts Building: C. 1980. A Reconstructed Inventory.
William Whitaker.
Curator and Collections Manager
Architectural Archives, University of Pennsylvania.

ARTS BUILDING: c. 1980

A Reconstructed Inventory

January 9, 2017
Compiled by William Whitaker

The inventory presented here is based on historic photographs taken in the mid to late 1970s through to the early 1980s – the period in which Nakashima wrote his seminal book, Soul of a Tree. That publication includes insightful statements about the building and collections, in addition to providing a number of important documentary photographs. Subsequent publicity related to the book produced additional photographic documentation making this time period a fertile one to reconstruct. However, this list would not have been possible without the discovery of a notebook entitled, “museum notes.” This item includes about 10 pages of notes about the contents of the building created by Mira Nakashima around 1977. It is an invaluable record of the contents of the building from furniture to folk art, and sculpture to wood slabs.

01. EXTERIOR – WESTERN APPROACH

[Arts Building exterior – permanent installation]

Ben Shahn
Poet's Beard (1970)
Mosaic (executed by Gabriel Loire from an original Ben Shahn gouache)

[Arts Building exterior – permanent installation]

Masayuki Nagare
Keyhole (1963-64)
Matsukage stone from Hagi, Japan

[Cabinet sold to Este Stowell in the 1980s]

8' French Walnut Cabinet with Table Lamp (lamp unlocated)

[North wall above cabinet – NOW @ Mira's]

Ben Shahn
Maximus of Tyre (1963)
Serigraph in black with hand coloring
Paper size: 36 x 26 ¼ inches
Nakashima frame size: [t.k.]
Signed, "Ben Shahn" in red with brush (lower right) – orange / red chop to left of signature

[NOW in fireplace niche]

02. INTERIOR – "CAVE," north wall

BLACK LACQUER PLATE
Note: “hand-carved, Mingei-style, from Takamatsu” on typed label affixed to underside of piece

[NOW in fireplace niche]


GOLD LACQUER PLATES IN BOX
Note: “Modern Japanese” on typed label affixed to underside of piece (box + top with 5 plates inside)

[vestibule wall opening]

Harry Bertioa
[Dandelion], 1960
[Bronze welded brass welded]
Note: “Kevin 1964 on bottom”

03. INTERIOR – “CAVE,” east & south walls

[East wall, above bench, short wall - @ Mira’s]

Ben Shahn
I Think Continually of Those Who Were Truly Great (1965)
Serigraph in brown and white with hand wash and hand coloring
Paper size: 26 ½ x 20 ¾ inches
Nakashima frame size: [t.k.]
Signed, “Ben Shahn” in black with brush lower right to the left of red chop

[NOW in Conoid Studio]

8’ American Walnut “R” Bench

[NOW in fireplace niche]

Cast Iron Skillet or pot (sitting on bench, possibly as ash tray)
Note: not found on Mira’s inventory, but in the 1967 photographs, as well as in later images.

04. INTERIOR – “CAVE,” west wall niches

[west wall, left alcove – NOW @ Mira’s]

Ben Shahn
Ecclesiastes (1966)
Serigraph in sepia with black calligraphy
(unspecified edition; 10 known)
Paper size: 22 7/8 x 17 ¾
Nakashima frame size: [t.k.]
Signed, “Ben Shahn” in black conté crayon upper left under orange-red chop

[West wall, second alcove – in Arts Building]

Ben Shahn
Gandhi (1965)
Serigraph in black
Paper size: 40 1/8 x 26 inches
Nakashima frame size: [t.k.]
Signed, “Ben Shahn” in red with brush (lower right) – orange / red chop top left
Note: inscription at lower left “For Kevin and George and Marion and Mira”
[West wall, large alcove – NOW @ Ru’s house]

Ben Shahn
Poet (1960)
Serigraph in two shades of brown
Paper size: 40 5/8 x 27 ½ inches
Nakashima frame size: [t.k.]
Signed, “Ben Shahn” in red with brush lower right

[fireplace mantle]

Jap Cast Iron Candlesticks
Note: originally installed flanking Ben Shahn’s Poet in vestibule niche

[West wall, alcove adj. closet – Now @ Kevin’s]

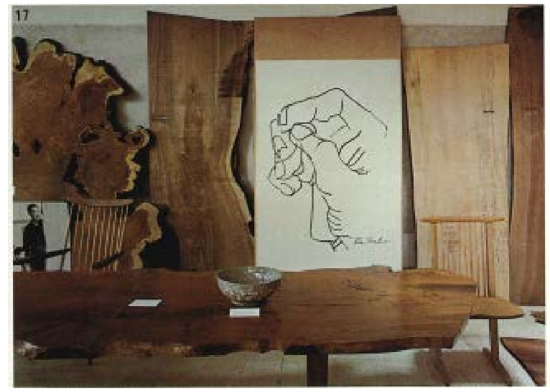
Ben Shahn
Branches of Water or Desire (1965)
Serigraph in black Paper size: 26 3/8 x 20 ½ inches
Nakashima frame size: [t.k.]
Signed, “Ben Shahn” in red with brush (lower right) – orange / red chop lower center right

05. LIGHT SCULPTURE

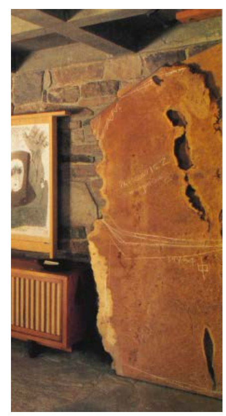
“Light Sculpture”
Note: Comprising of two book-matched slabs of English walnut (measuring 12’ tall) and one English Oak burl. The latter slab was sold in the 1980s. The English walnut slabs were reconfigured into a revised configuration for the Light Sculpture.

06. SLABS OF EXOTIC WOODS ACCOUNTED FOR IN MIRA’S INVENTORY

Note: All were shown in Cave or Gallery, the juxtaposition of wood slabs and furniture is exceptional



English walnut [10 slabs]; American maple; Persian walnut [3 slabs]; East Indian Rosewood; Carpathian elm; Black Walnut; East Indian Laurel; Buckeye Burl; Redwood Burl; Walnut burl; English Oak burl



Left: “Two walnut Conoid Chairs…stand… before an extraordinary piece of buckeye burl wood” [p. 169, Soul of a Tree]

Right: English oak burl near French Walnut Cabinet [p. 39, Soul of a Tree]

07. INTERIOR – "GALLERY"

[Arts Building, main room]

MINGUREN IV DINING TABLE (1967)
English oak burl and East Indian laurel
[dimensions t.k.]
Markings: "Museum" (in marker) / "III" / "Mira 1969"
Note: "Mate" of this table located at Ritsurin Garden's *Shoko Shoreikan* (Commerce and Industry Promotion Hall), in the *George Nakashima Room* on the second floor / link to Takamatsu

[NOW in Conoid Studio

New Chair with Arms, "Ben's Chair" (1965)
Walnut
Note: Mira's inventory states, "Ben sat here; once reserved for Ben who in the interim, passed away / SR"
Markings: "Kevin 1966" in marker on bottom of seat (1965-CH-25)
Note: many photos show this chair positioned with the Minguren IV table and in front of Ben Shahn's hand drawing from Parry Barn exhibit

[Main room, leaning against wall]

Ben Shahn
Hand (1963)
Photographic reproduction of original ink drawing given to Nakashima's created for Parly Barn exhibit in 1963 – usually close to Minguren IV table and "Ben's Chair"

[NOW in loft niche]

GRAY POTTERY BOWL
Note: "Turned but free form during stamping and glazing. Eccentricity accentuates beauty" on paper label affixed to bottom. Japan stamp on bottom.
Note: shown on Minguren IV table in a number of photographs of this period

[Arts Building, main room – NOW Mira's]

Floor lamp [generic image]
Markings: “Kevin 1967” on bottom
Note: usually near Minguren IV, towards fireplace side.

[Arts Bldg., main room]

CONOID CHAIR (1967)
Teak
Markings: “Arts Bldg” and “Kevin 1967” in marker on bottom of seat (1967 CH-22)
Note: often paired with Rosewood against East wall near end of Minguren IV table

[Arts Bldg., main room]

CONOID CHAIR (1967)
Rosewood
Markings: “Arts Bldg” and “Kevin 1967” on seat bottom in marker / partial label (1967 CH-21)

[SOLD to Connie and Tully Patrowicz]

To be located

CONOID CHAIR (date t.k.)
Oak
Markings: to be determined
Note: This one may be the Conoid chair usually paired with “Ben’s Chair” on the north side of the Minguren IV table.

[Arts Bldg., main room]

CONOID CHAIR (1967)
Walnut
Markings: “Studio” and “Mira 1967” in marker on bottom of seat (1967 CH-19-number repeated)
Note: The two walnut Conoid Chairs may have been placed at a distance from the Minguren IV table

[Arts Bldg., main room]

CONOID CHAIR (1967)
Figured Walnut
Markings: “Studio” and “Mira 1967” located on bottom of seat in marker (1967 CH-19 – number repeated)

[Arts Building, main room]

Large English Walnut Bench [extraordinary slab]

Look photos 1958 Kevin & G (photo Rothsein)

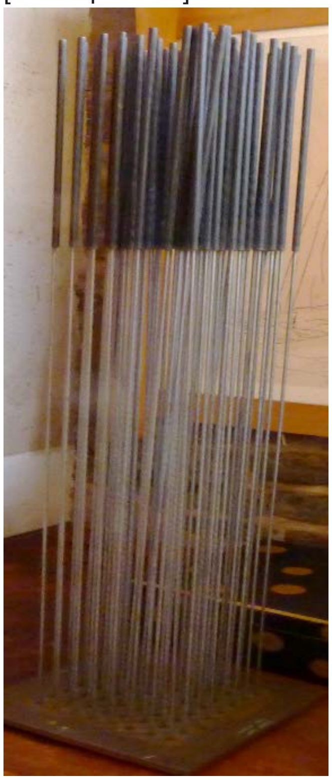
[vestibule niche]

Holland Photo (George 1955)
In Mira Nakashima Frame
Note: Both this and the photo below are usually seen leaning against wood slabs in the gallery. Framed and hung in the 1990s

[Under stair]

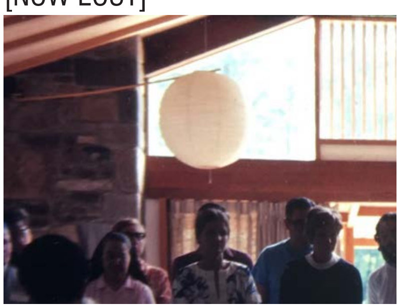
08. INTERIOR – GALLERY, PLATFORM AND SLIDING DOOR AREA

[corner platform]



Harry Bertioa
[Sounding Piece], 1974
[Beryllium copper, brass plate]

[NOW LOST]



Isamu Noguchi
“AKARI” LIGHT SCULPTURE
Washi paper and bamboo
Approx. 22” in diameter hung 80” off floor
Note: this image was taken in 1969 and likely shows the original paper lamp.

[Not located]

Conoid Cushon Chair with Japanse Kasuri fabric
Note: image from 1972 Smithsonian article. An example of this chair can be found in Mira’s House and may be this on, but reupholstered. Note:

[Not located]

Conoid Cushon Chair with “Beige” fabric
Note: this image is reversed. It is likely that the Conoid Cushion chair was paired with a second unit, with yellow fabric (see image from Parry Barn exhibition)

09. FIREPLACE SEATING AREA

[Fireplace area]

SETTEE, NO ARMS (1956)
American black walnut, upholstery, plywood, maple (handwoven upholstery fabric by Eleanor Gordon)
52 ¼ x 49 x 35 inches
Markings: “Kevin 1956” (underside)
Note: Full Circle, p. 146-47
Note2: This example is probably the piece photographed in the Showroom and used there for a period of time.

[Fireplace area]

MINGUREN I COFFEE TABLE (1968)
English oak burl
15 7/8 x 29 ¾ x 70 inches
Markings: “Kevin 1970” (underside)
Notes: piece is not visible in 1967 photos
Note: Full Circle, p. 132-33

[Arts building, main room]

LOUNGE CHAIR WITH ARM (RIGHT)
Walnut
Markings: “George Nakashima, June 1968” / “Kevin 1968 / Arts Bldg.” in marker on underside of seat

[NOW IN SHOWROOM]

LOUNGE CHAIR WITH ARM (LEFT)
Walnut
Markings: “Kevin 1968 / Arts Bldg.” in marker on underside
Note: sap line and cavity in arm match photographs of this piece in Arts Bldg.

[Fireplace area]

LOUNGE CHAIR (no arms)
Walnut
Markings: “Mira 1966” on underside (1966-CH-27)

10. FIREPLACE AND NICHE

[NOW in Conoid Studio]

1 holy candle holder [carved by Santiago Riva of Santiago, Spain – candleholder at Martin's, New Hope / This one was rejected – had a knot hole so was retained by GKN]
Note: sat on window sill.

[Not hung, leaning in Fireplace niche]

CAST IRON POT HANGER
Antique from Takamatsu, Japan
From <u>Soul of a Tree</u>, p. 34: "Adjustable pothooks, called *jizai-kagi*, hang over the central hearth in many Japanese farmhouses. The motif of adjusting height in this one, which is in our Minguren Museum, is typical – a fish."

[Now in loft niches]

ANTIQUE EUROPEAN STAINED GLASS
Glass and metal
Note: "Gift of Father Peter [Sidler] Portsmouth, Rhode Island"
Note: hung in pane of casement sash in niche / artist and priest at Portsmouth Priory; designed the doors to the Church (P. Belluschi) and Nakashima the furnishings (groundbreaking on Nov. 21, 1958; finished by about 1960). This is a touchstone at the beginning of his work for the Catholic Church.

[NOW @ Mira's]

Ben Shahn
And Mine Eyes a Fountain of Tears (1965)
Serigraph in red with black Hebrew calligraphy
Paper size: 23 7/8 x 17 7/8 inches
Nakashima frame size: [t.k.]
Signed, "Ben Shahn" in black with conté crayon
Note: hung on west side of fireplace niche

[NOW @ Reception]


Ben Shahn
Wealth [date unknown]
[Iomo (orig. ink calligraphy)]
Size:
Signed: “With love for George and Marion from Bernarda & Ben”
Note: The piece was moved to the Reception House upon that buildings completion in 1977
Note: hung above fireplace

11. UNDER FIREPLACE

[Fireplace area – movable]


TATAMI PLATFORM (1967)
Walnut and 3 tatami mats
10 x 111 ½ x 75 ½ inches
Note: piece is movable and has been positioned askew in the room, under the skylight, for performances and special events.
Note: This piece can be moved and used in the main space of the Gallery for performances

[5 on window seat, 4 on bench in loft]

NINE CUSHONS
Cushon covers, Japanese handwoven fabric “Kasuri” Threads are dyed before weaving

[NOT LOCATED]

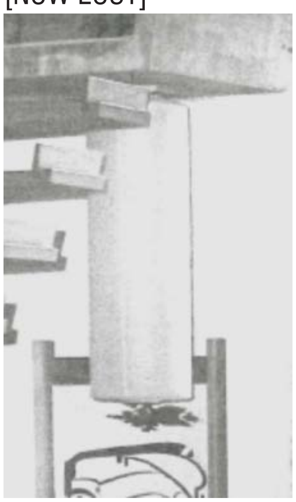
LINEN COVERED CUSHIONS
Note: 1967 photographs show 6 cushions in a variety of colors. Mira recalls colors as blue and white. Two cushions are shown in the photo above.

[NOW near door]

Ben Shahn
Byzantine Memory (1966)
Serigraph in black and brown with hand coloring
Paper size: 26 3/8 x 30 ½ inches
Nakashima frame size: [t.k.]
Signed, "Ben Shahn" in black conté crayon lower right and orange-red chop upper left
Note: inscribed, "Happy Birthday to George", hung under the stair

Basket from Japan
Note: shown sitting on the built-in bench near fireplace in early photos.

[NOW LOST]



Paper lamp
Note: hung under the stair

[loft floor]

12. LOFT – BUILT-IN FURNITURE

[loft, built in]

Conoid Bench with Double Back, built-in

[loft, built in]

Slab Side Table, built-in

Desk Lamp

[Loft area, permanently installed]

Kiyoshi Konishi
Hexagonal Shoji
Port Orford Cedar (American Cypress) or “Beihi”
Takamatsu, Japan

[loft, on top of side table]

13. LOFT RAISED PLATFORM

[currently in main room]

Kent Hall Lamp [generic image], 1964

[Loft]

LONG CHAIR (1951)
Walnut, cotton webbing, sea grass
31 ¾ x 34 x 68 inches
Note: Mira noted in this inventory that it was "unfinished wal." Confirming that this is the piece on view in the Arts Building.
Note: Full Circle, p. 150-51

[vestibule]

SLAB COFFEE TABLE (original; 1949)
American black walnut
12 ¼ x 56 x 17 inches
Note: Full Circle, p. 118-19
[loft]

FITCH STOOL (1954)
Walnut with twisted grass seat
20 x 20 x 13 inches
Note: "Mira 1972" on bottom

[NOT LOCATED]

PLANK STOOL (1954)
American black walnut
Markings: "Kevin 1954" on bottom

[vestibule]

Original 4 legged chair, flat seat, cherry designed as a piano chair for Mira about 1954
Markings: “Mira 1954” on bottom (1954-CH-09)

[loft]

Left: LOW MIRA CHAIR (1950)
American black walnut, poplar
24 ¾ x 19 ¼ x 17 5/8 inches
Markings: “Mira” and signed “George Nakashima, New Hope, PA” on bottom of seat

Center: MEDIUM MIRA CHAIR (1956)
American black walnut, poplar
28 ¼ x 19 ¾ x 19 ½ inches
Markings: “Kevin 1956” on bottom of seat
Note:

Right: HIGH MIRA CHAIR (1952)
American black walnut, poplar
33 x 19 ¾ x 19 inches
Markings: “Mira 1952” on seat bottom (1952-CH-02)
[loft]

STRAIGHT BACK CHAIR (1950)
[cherry?]
Markings: “Mira 1950” on bottom with “Arts” in marker

[loft]

ARM CHAIR (1958)
[material]
Markings: “Kevin 1958” on bottom (1958-CH-10)

[loft]

NEW CHAR (original)
Walnut with poplar seat and hand shaved hickory spindles
Dimensions: 16 ¼ x 18 ¼ x 35 ¾ inches
Markings: “Mira 1955” on bottom; label note “personally made by GKN” (1955-CH-12)

loft]

NEW CHAIR (1968)
[Walnut with hickory spindles]
Dimensions: 16 ¼ x 18 3/8 x 35 5/8 inches
Markings: “Kevin 1968” on bottom (195x-CH-14)

14. LOFT NICHES – WORKS TIED TO MINGUREN AND KIYOSHI KONISHI

Note: Konishi was a GKN collaborator and a Minguren member.

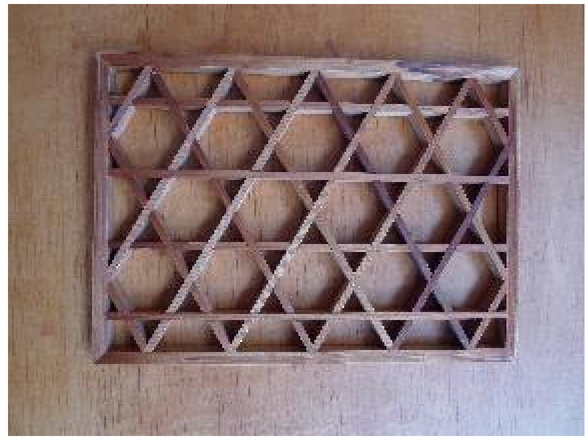
[loft niches]

Commemorative “Getta” Wooden Clog
“Traditional Japanese footwear (minus Thongs). Signed by members of the Seisaku-sho & “Minguren” in 1965”
Japan

[Now on bedside table in Cloister]

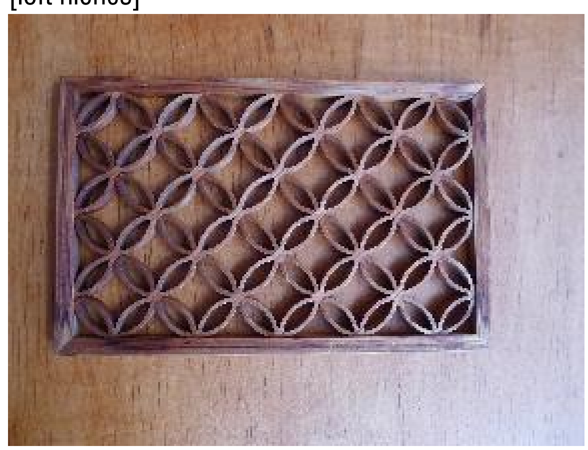
Kiyoshi Konishi
DESK LAMP
Washi paper and wood
Note: Kevin N. recalls that these were made in Japan by Konishi Mokkō. They arrived as kits, assembled and sold by GKN.

[loft niches]



Kiyoshi Konishi
Shoji Screen Sample – Hexagonal configuration
“Made of Port Orford Cedar (American Cypress) or “Beihi” in Takamatsu, Shikoku, Japan. Fine examples of a very precise art handed down for generations. Now limited by the skills of fewer people in Japan.”
Note: Mira’s notebook refers to maker as Konishi Mokkō. The latter is Company in Japanese. Kiyoshi Konishi was a collaborator with GKN and a Minguren member.

[loft niches]



Kiyoshi Konishi
Shoji Screen Sample – Round configuration

15. LOFT NICHES – JAPANESE FOLK OBJECTS AND FOLK ART

[loft niches]

Antique lumber saw
Takamatsu, Japan

[loft niches]

Metal Brands [2 items]
“A & B (For burning designs into wood)

[loft niches]

Bamboo Salt and Pepper Shakers
“An example of the skillful adaptation of Japanese technology to Western necessities”
[loft niches]

Paper Mache Folk Toys [9 items]
“These are examples of traditional folk toys of Kagawa Prefecture made by a little old lady in Takamatsu. Acquired in 1962. Her daughter carries on her work now.”
Takamatsu, Japan

[loft niches]

Wooden head rest used by Geisha [2 items]
Japan

[loft niches]

1 basket and holder for flowers
[loft niches]

“Hakosumitori” charcoal container used in the preparation room for a tea ceremony
Takamatsu, Japan
Red Pine

[loft niches]

JAPANESE BASKET SIEVE

[loft niches]

1 teapot, disposable [ceramic]
Note: top serves as cup for drinking, as shown here. 3 pieces (top, pot, and saucer)

[loft niches]

Cast Iron Tea Kettle
Japan

[loft niches]

Wood Cut Block, “An example of the delicate block-printing technique perfected in Japan. It was an entire page from a book.”

[loft niche]

Turtle mold for cake (2 pieces)

[loft niche]

Crab mold for cakes (2 pieces)

[loft niche]

Flower cake mold (2 pieces)

[loft niche]

Cake mold (1 piece)
[loft niche]

[loft niches]

Wood Shaving Owl. “Example of traditional Japan Folk Art ([donated by] Ezra Stoller)
“Craft Center Japan” label Japan

16. LOFT NICHES - FOLK ART OBJECTS FROM INDIA

[NOT LOCATED – LOST]

To be located

Crude clay figure with fruit on head (folk Art from Ahmedabad) from “Hakubai”

[loft niches]

“Carved Wooden Horse”
India

[loft niches]

Wooden Printing Blocks for Textiles (9 items)
“From Ahmedabad, India”

[loft niches]


3 wooden bowls from Jain monastery Ahmedabad
Note: Period photographs show these on display in a “nested” configuration.


Carved Wooden stand
Teak

[loft niches]

Copper pot antique bronze

[loft niches]

Piece of antique architectural screen from ancient part of Ahmedabad

[loft niches]

Bowl from India – contributed by Gita Sarabhai
[loft niches]

[loft niches]

Insense basket (india)
[loft niches]

Indian Bead-pillow hanging

Notes: a Catholic Benedictine monk from Mount Saviour Monastery in Elmira, NY / very involved in interfaith groups

[loft niches]

Wood from Brother David
Note: are we sure this the small English oak burl on the mantle?

17. LOFT NICHES - GIFT FROM BROTHER DAVID STEINDL-RAST

18. LOFT NICHES - FOLK ART OBJECTS GIVEN BY BEN SHAHN

[loft niches]

Ben Shahn
Four Model Buildings made by Ben Shahn for his children's model railroad and then given to Kevin Nakashima
Note: "Sunset Hotel / Harvey House; church; wood house; stone house

[loft niches]

Pig in a Poke
Carved Hand-Painted pig in a basket given by Ben Shahn / from Southeast Asia

[loft niches]

CEREMONIAL DOLL
"Made of straw and filled with grain, it was used in a ceremony to insure good crops in Southeast Asia." Gift of Ben Shahn

[NOW LOST]

Now lost

3 Ben Shahn eggs
Painted
Note: Began rotting and had to be thrown away. Mira recalls that these were "vividly painted." one had a "face" and the other, "spots." All of the designs were on a white background.

19. LOFT NICHES - FOLK ART OBJECTS GIVEN BY NITA AND STANLEY BROGREN

Stanley Brogren and GKN went to high school together in Seattle, as well as to Univ. of Washington for architecture (both graduated with B.A.'s in 1929). Nita was a sophomore in their senior year and worked professionally as an interior designer. Nita designed the paper lamps in the Showroom as well as the frock that Mira wore for the Look Magazine photoshoot for the article "A Chair for Mira."

[loft niches]

CARVED WOODEN BIRDS MOUNTED ON WOODEN BURL (possibly by Mira Nakashima)
Gift of Stanely Brogren

[loft niches]

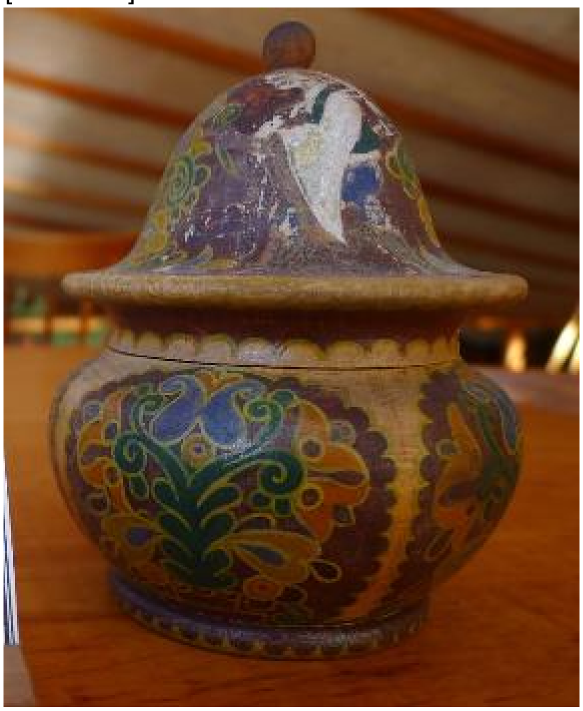
CARVED WOODEN DECOY DUCK
"An early American antique"
Gift from Nita and Stanley Brogren

[loft niches]

Antique Bronze Teapot (silvered) from Persia
Gift of Stanley Brogren

20. LOFT NICHES - HERILOOMS FROM OKAJIMA AND NAKASHIMA FAMILIES
Note: Given by Marion Nakashima's aunt Masa Okajima or owned by her mother.

[loft niches]



PAINTED WOODEN JAR WITH LID
"From Budapest from Aunty Masa"

[loft niches]

ANTIQUE CERAMIC CANDY DISH
"From Aunty Masa Okajima, Japan about 1900"

[loft niches]

ANTIQUE COPPER TEAPOT
Note: "From Japan about 1890. Formerly owned by Marianne Hecht Okajima, Marion's mother."

[loft niches]

TRAY FROM INDIA
Brass
Note: "A wedding gift to George and Marion from India, Feb. 14, 1941"

[Now at Mira's House]


Totem pole – Hudson Bay fan co., Seattle, WA

[loft niches]

Mask?

21. LOFT NICHES - GIFTS FROM TOM AND MARY MURAKAMI
Notes: Mira recalled that the Murakami's were "very good clients" and family friends. Tom worked for RCA and made important contributions to the creation of color TV as well as Naval radar systems. Tom and Mary lived in Kualajin from 1974 to 1978 where the Navy tested radar systems. They may have made more trips to that area. Tom (Tomomi) and Mary (nee Doi) were born in California and as Japanese Americans at the outbreak of WWI, were incarcerated at camps in Arkansas and Wyoming respectively.

[fireplace niche]

JAPANESE GLASS FLOATS
Marshall Islands, 1960
Note: "Roller float is a rare one….Gift of Dr. and Mrs. Tom Murakami"

[fireplace niche]

GLASS FISHING FLOAT
Kualajin, South Pacific
Note: "From Dr. and Mrs. T. Murakami"

[fireplace niche]

HAND WOVEN SHELL BASKET
Note: "From the Marshall Islands Gift, Dr. & Mrs. Murakami, 1979" / this is not on Mira's inventory – supporting that the list dates from c. 1976-78 / included on this list because of close connection btwn Naka's and Murakami's.

22. CLOISTER

[cloister room]

Dorothy Grotz

Bois de Boulogne (?)

Oil on canvas mounted in Nakashima frame

[East wall, Cloister room]

2 wall hangings from India – acquired in Ahmedabad, 1964

2 wall hangings from India – acquired in Ahmedabad, 1964

[Cloister room, west wall]

Isamu Noguchi

“AKARI” LIGHT SCULPTURE

Washi paper and bamboo

[size t.k.]

Note: check interior to see if it is a Noguchi Akari lamp – signature + moon in red is expected

[South wall, Cloister room]

Appendix I

National Historic Landmark nomination, February 2013

1. NAME OF PROPERTY

Historic Name: George Nakashima Woodworker Complex

Other Name/Site Number:

2. LOCATION

Street & Number: 1847 and 1858 Aquetong Road Not for publication:

City/Town: Solebury Township Vicinity:

State: Pennsylvania County: Bucks Code: 017 Zip Code: 18938

3. CLASSIFICATION

Ownership of Property		Category of Property	
Private:	X	Building(s):	X
Public-Local:	___	District:	___
Public-State:	___	Site:	___
Public-Federal:	___	Structure:	___
		Object:	___

Number of Resources within Property

Contributing	Noncontributing	
17	2	buildings
___	___	sites
2	___	structures
___	___	objects
19	2	Total

Number of Contributing Resources Previously Listed in the National Register: 19

Name of Related Multiple Property Listing: Nakashima, George, House, Studio & Workshop

4. STATE/FEDERAL AGENCY CERTIFICATION

As the designated authority under the National Historic Preservation Act of 1966, as amended, I hereby certify that this ____ nomination ____ request for determination of eligibility meets the documentation standards for registering properties in the National Register of Historic Places and meets the procedural and professional requirements set forth in 36 CFR Part 60. In my opinion, the property ____ meets ____ does not meet the National Register Criteria.

Signature of Certifying Official Date

State or Federal Agency and Bureau

In my opinion, the property ____ meets ____ does not meet the National Register criteria.

Signature of Commenting or Other Official Date

State or Federal Agency and Bureau

5. NATIONAL PARK SERVICE CERTIFICATION

I hereby certify that this property is:

__ Entered in the National Register
___ Determined eligible for the National Register
___ Determined not eligible for the National Register
___ Removed from the National Register
___ Other (explain):

Signature of Keeper Date of Action

6. FUNCTION OR USE

Historic: Domestic-single dwelling Sub:
Commercial/Trade-professional
Industrial/Processing/Extraction-manufacturing facility
Recreation and Culture-museum

Current: same Sub:

7. DESCRIPTION

ARCHITECTURAL CLASSIFICATION: Modern Movement (Japanese-influenced International Style)

MATERIALS:
Foundation: concrete
Walls: concrete, concrete block, stucco, stone, wood, glass
Roof: wood, transite, reinforced concrete, warped plywood shells
Other:

Summary

George Nakashima is one of America's most eminent furniture designer-craftsmen and a significant force within the American Craft movement of the mid-twentieth century, a seminal period for woodworking in the United States. Nakashima and others within the new movement rejected the mass-production brought on by the machine age and industrialization while at the same time embracing Modern stylistic influences and ideas that were international in scope. Often defined as "organic naturalism," his timeless pieces defy stylistic categorization. Believing in the spiritual qualities of wood, Nakashima's signature features incorporated techniques intended to enhance the impact of the wood's natural beauty, such as the "free-edge" and the use of butterfly inlays. His success as an artisan propelled him briefly into the arena of mass-production; from 1945 to 1954 internationally recognized modern furniture manufacturers Hans and Florence Knoll produced a selection of Nakashima's designs, which appeared alongside other noted modernists including: Franco Albini, Harry Bertoia, Pierre Jeanneret, Ludwig Mies van der Rohe, Isamu Noguchi, Eero Saarinen, and Florence Knoll herself. However, Nakashima saw furniture making more as a spiritual journey, crafting unique pieces that responded to the natural form of each piece of wood. His work expresses a worldview that is based upon a unique set of circumstances including his formal education in architecture, his exposure to European Modernism, eastern religious philosophy, and traditional Japanese craft traditions, including instruction from Issei carpenter Gentaro Hikogawa while confined to a Japanese-American Internment Camp. He began his professional career as an architect, working at the vanguard of International Modernism in Japan before turning to furniture design. Thus, Nakashima is also responsible for the design and construction of the structures that comprise the Nakashima Woodworker complex, erected between 1946 and 1982. Designed in the International Style intermingled with elements of traditional Japanese architecture and featuring the innovative use of concrete, the buildings and structures in the complex are treasures of Nakashima's unique legacy of craftsmanship and design excellence.

Describe Present and Historic Physical Appearance

The George Nakashima Woodworker site is located at 1847 and 1858 Aquetong Road, Solebury Township, Bucks County, Pennsylvania. The property consists of a complex of buildings on both sides of Aquetong Road on two tax parcels. On the south side is a nine-acre, partially wooded, parcel that contains eighteen resources including the George Nakashima House (1946), the Workshop (1946), the Showroom (1954), the Finishing Department (1955), the Main Lumber Storage Building (1956; 1968), the Chair Department (1957), the Lanai (1958), the Pool Storage House (1958), the Pool House (1960), the Swimming Pool (1960), the Conoid Studio (1957-60), the Arts Building and the Cloister (1964-67), the George Nakashima Garage (1967), the Reception House (1975-77), the Heating House (1977), the New Lumber Storage Building (1982), and the Pole Barn (1990). On the north side of Aquetong Road on a partially wooded three-acre parcel are the Mira Nakashima House (1970), the Mira Nakashima Guest House (1971), and Mira Nakashima Garage (1985). There are twenty-one resources total on the property, nineteen of which were designed and constructed by George Nakashima and are contributing; only the Pole Barn and the Mira Nakashima Garage are noncontributing. The buildings and structures generally reflect the International Style with some also possessing traditional Japanese influences. All of the buildings (on both tax parcels) were designed by George Nakashima, who also had a hands-on role in the construction of most of the buildings. Materials used include stone, cement block, concrete, glass, stucco and wood. Some of the roof types also constitute unique and unusual engineering systems. These include a conoid shell roof which is a shape generated from a section of a cone; a hyperbolic paraboloid which is a saddle-shaped surface, and a scissors truss, which is a truss that is asymmetrical resembling a partially open pair of scissors. The buildings and the setting retain physical integrity and continue to be used for a variety of purposes including residences, education, production, storage and administration related to the legacy of internationally known furniture craftsman George Nakashima.

The Site

The setting for the property consists of sparsely wooded areas with intermittent open mown areas; approximately 50 percent of the property is open space. A gravel driveway and footpaths are the primary means of vehicular and pedestrian circulation within the complex of buildings. Generally, there is not signage for pathways or on buildings. After entering the complex, there is a small parking area to the right (west) for workers and visitors. Many of the buildings are built along a south facing ridge and have large windows on the south facing side allowing natural light and heat into the buildings and providing a view of open mown areas, scattered trees, and densely wooded areas. Buildings are spaced relatively far apart but in a linear cluster on the northern half of the property along the ridge not far from Aquetong Road. Buildings used for processes and workshops are clustered closest to Aquetong Road, lumber storage buildings are along the northern boundary of the property and buildings with residential and administrative uses are toward the center and east parts of the property. The buildings with administrative and residential functions including the Reception House, George Nakashima House, Showroom, and Conoid Studio, are entered from the rear or north side with the front or south side facing onto the open areas. The buildings are not physically or visually separated from each other. For example, the main storage building is immediately adjacent to the Reception House. There are small ponds, boulders, stone walls, patios and paths dispersed among the buildings. George Nakashima and his father planted trees from the Pacific Northwest on the property to remind him of his homeland. The driveway for the property crosses Aquetong Road and connects to the Mira Nakashima property, which also has scattered trees, wooded areas and a small pond.

Arts Building (contributing building; map #1)

The Arts Building was completed in 1967 in the International Style and was constructed as an art gallery and museum to display works by Ben Shahn. It continues to serve as a museum that also displays artifacts associated with George Nakashima. The building is about two-and-a-half stories tall and measures approximately 36' x 40'. Its roof is a hyperbolic paraboloid constructed of plywood covered with asphalt. Walls are constructed of concrete block, stone and poured concrete. Large sections of the west and south sides are glass windows. Along the west wall on the first floor of the building is a tile mosaic designed by artist Ben Shahn. The south side of the building has two entrance doors, one near the southwest corner and the other large sliding doors leading out to the covered walkway. The interior of the building features a cantilevered floating staircase that leads to a mezzanine. The staircase has no outside rail and no risers, and the ends of the steps are secured deeply into a thick stone wall. Many examples of Nakashima’s work are in the building.

Cloister (contributing building; map #1B)

Connected to the arts building by a covered walkway, the Cloister is a small, one story, rectangular-shaped building. It has a shed-type roof covered with asphalt. Walls are constructed of cement block. There are three wood entrance doors with horizontal glass panels. The interior features rice paper screens over windows, exposed beam ceilings, and plaster walls. The Cloister contains a bedroom, bathroom, kitchen, and storage room. The International Style Cloister was planned and constructed more-or-less simultaneously with the Arts Building (1964-67).

Conoid Studio (contributing building; map #2)

With a distinctively designed reinforced concrete conoidal shell roof, the Conoid Studio provides work areas for the design of furniture as well as space for education and training. The concrete roof is approximately 2-½" thick and has sinusoidal waves beginning on the northern side of the building that flatten towards the southern side of the building. The sinusoidal waves are not only aesthetically pleasing, but are key to the support and structural engineering of the building. There is an arched buttress that supports the roof along the southern façade. The building is constructed into a south facing hillside and cantilevered from a basement wall. It measures approximately 40' x 40'. Materials used on the walls of the studio include cement block, stone, stucco, and glass. The roof of the building is constructed of poured concrete with reinforcing rods and wire lath. The non-weight-bearing upper walls are constructed of light frame. The interior of the building includes a large open area with kitchen, bathroom and a design office area. The south-facing windows allow for a maximum amount of natural light partially filtered through rice paper screens. Floors are wood and the ceiling exposes the same sinusoidal curves of the exterior. There is a *tatami*, or raised platform with grass mats, located in a rectangular bay that cantilevers outward from the building on the south side. A large rice paper “Akari” lighting sphere by Isamu Noguchi is suspended from the ceiling. Numerous Nakashima designed chairs and tables are used in the room. Construction of the Conoid Studio began in 1957 and was completed in 1960. It is International Style. It is counted as a contributing resource to the property.

Chair Department (contributing building; map #3)
The Chair Department was originally built as a clubhouse for workers. However, soon after it was built it was converted to space for assembling chairs. The building, the same form as the Conoid Studio, has a conoidal shell roof made of plywood. The Chair Department was built in 1956 as a smaller prototype for the larger Conoid Studio built the following year. The Chair Department, however, does not have the sinusoidal waves in the roof. Overall the building measures approximately 25' x 20' and is nearly two stories high at the south side. Since the building is cantilevered into the hillside, it is one story on the north side. Materials of the walls include stucco, concrete block, wood, and glass. It is a contributing building.

Finishing Department (contributing building; map #4)
Originally built for lumber storage, the Finishing Department was quickly converted for use as a building where finish is applied to the furniture. It was built in 1955 and is also International in style. The building is counted as a contributing resource. The roof over the main part of the building is a slightly sloped gable, covered with plywood and asphalt. There is also a shed roof over a wing that is covered with corrugated Transite, which is a composite of asbestos and concrete. The walls are constructed of cement block and wood. The south side consists almost entirely of large glass windows.

Showroom (contributing building; map #5)
The Showroom was constructed in 1954, specifically for use as an area to put examples of the furniture on display and as the business office. The building has a gently sloped gable roof supported by recycled barn beams that is covered with corrugated Transite. Wall materials include stone, wood and stucco. The building is trapezoidal in shape and has a covered wood deck and patio. Sliding rice paper screens lead to the wood deck and to an entryway that leads to the patio. The interior features a *tatami* platform, cherry wood floors, a small fireplace, a hanging cabinet, and wall lights designed by Nakashima. In addition to the open showroom area there is also a bathroom, office and kitchen area now used as office space.

Workshop (contributing building; map #6)
The Workshop is where the furniture is manufactured. The original section of the Workshop was constructed in 1946 with additions made to the building in 1959, 1970 and 1988. The original 1946 section of the Workshop is contained in the eastern most part of the building. In 1959 the original section of the Workshop was expanded by an addition on the west side. In 1970 the northern part of the Workshop was added and the carport to the east, later modified to shop space. The Workshop has a gable roof with a projecting clerestory added in

1985. The roof is covered with corrugated Transite and asphalt. Wall materials are wood, stucco, Transite, glass and cement block. It is irregular in shape measuring roughly 65' x 60'.

George Nakashima House (contributing building; map #7)
Built in 1946, the George Nakashima House served as the primary residence for the Nakashima family and is currently used as a residence by Kevin Nakashima, George's son. A small addition was built onto the house in 1954 for a bedroom. The house has a gable roof covered with wood shingles built in 1982 over the original poured concrete tile roof, expanding the house three feet to the south. Walls are stucco, stone and wood. It measures roughly 55' x 15' and is one story in height. The interior of the house features natural un-milled support posts, large recycled beams and hardwood floors. The living room has a fireplace and rice paper sliding doors that lead to a balcony that overlooks the open space areas of the property.

Heating House (contributing building; map #8)
The Heating House is a contributing building, measuring 17' x 9'. It was built in 1977 and is constructed of concrete block and wood. It housed the fuel and the wood-fired boiler for heating the George Nakashima House; the boiler has since been converted to oil.

Lanai (contributing structure; map #9)
The Lanai is a small structure designed for the Simpson Redwood Company to serve as outdoor living space. It was constructed in 1958 of California redwood with a cantilevered design and anchored in concrete. A stone barbecue is built into the structure. The roof is now covered with cedar shake shingles. It is counted as a contributing structure.

George Nakashima Garage (contributing building; map #10)
The garage is a small rectangular concrete block building with a gable roof covered with corrugated Transite. The walls are covered with stucco and it has a foundation of stone. It is a one-car garage with an overhead door and a round window. It also includes a laundry room and storage. The garage was constructed in 1967 and is a contributing building.

New Lumber Storage Building (contributing building; map #11)
The new lumber storage building was completed in 1982. The walls are constructed of cement block and it has a plywood and asphalt covered shed type roof. It is a contributing building.

Main Lumber Storage Building (contributing building; map #12)
Built in 1956, the main lumber storage building had an addition in 1968 and a small electric kiln addition in 1999. The main Lumber Storage Building features two hyperbolic paraboloid roofs made of plywood and covered with plywood and asphalt. Walls are constructed of cement block. It is a contributing building.

Reception House (contributing building; map #13)
The Reception House was built from 1975 to 1977 to serve as a guesthouse featuring a tea room and Japanese-style sunken bath; it continues to be used as a guest house and as a location for meetings. The roof of the house is covered with cedar shake shingles. The support system for the roof is a unique scissor truss design. Wall material includes stone, stucco and cement block. The interior features a living area with a fireplace, a dining area with a kitchen cleverly hidden behind sliding wood and rice paper screens and a tea room with a *tatami* floor. There is also a large, amoeba-shaped, sunken Japanese bath heated by a Japanese wood-burning boiler.

Pole Barn (non-contributing building; map #14)
Although designed by family members with an architect's background, due to its recent vintage, the pole barn is a noncontributing resource; it was constructed in 1990 with additions in 1995 and 2006. It is a very large building measuring roughly 45' x 180' and serves as a lumber storage building, containing the huge slabs of wood from which the Nakashima furniture is fashioned.

Pool Storage House (contributing building; map #15)
The Pool Storage House is used to store chemicals and equipment for the nearby Swimming Pool but was built primarily to serve as a prototype for the Pool House. It was built in 1958 and has a canted barrel vault roof made of plywood that rests on a cement block base. It is a contributing resource.

Pool House (contributing building; map #16)
The Pool House is a large building measuring 33' x 30' and is open at both ends. It was constructed in 1960 with a distinctively canted barrel vaulted roof design. The roof is constructed of plywood and covered with a thin layer of asphalt and edged with copper. The base of the Pool House is constructed of stone and concrete block. It is a contributing resource to the historic property.

Swimming Pool (contributing structure; map #17)
The Swimming Pool was built about the same time as the Pool house, in 1960, and won a prize for its amoeba shape with cantilevered overhang. It is constructed of reinforced concrete and is counted as a contributing structure.

Mira Nakashima House (contributing building; map #18)
The Mira Nakashima House was constructed in 1970 and is a contributing resource to the historic property. The building was designed and built by George Nakashima for his daughter Mira. It has a distinctive scissor truss roof design that is covered with cedar shake shingles. Wall materials include cement block, wood, and stucco. It has a concrete and wood deck across the main façade, accessed by a wood ramp. Large sliding doors lead from the deck to the house. The interior features an open floor plan, hardwood floors, with rice paper screened windows and a corner fireplace in the living area. The hardwood and linoleum floors are laid directly over the 3" x 8" structural members laid flatwise and project outside to form the porch. It has a kitchen, bath and four bedrooms.

Mira Nakashima Guest House (contributing building; map #19)
Built in 1971, the Mira Nakashima Guest House is a small building, the distinctive feature of which is its scissor truss roof design. The roof is covered with cedar shake shingles. Wall materials include stucco and cement block. It is a contributing building, but was restored and slightly reconfigured in 2008 by Mira.

Mira Nakashima Garage (non-contributing building; map #20)
The Mira Nakashima Garage was built in 1985. It was not designed or built by George Nakashima and is therefore a noncontributing building. It has a cedar shake roof and vertical wood siding.

Statement of Integrity

The George Nakashima House, Studio, and Workshop complex retains a high degree of historic integrity. Very few noncontributing resources are located on the property; with few exceptions most of the buildings remain unaltered and the setting and overall landscape of the property is outstanding. The noncontributing buildings on the property have designs that fit with the existing buildings. For example, the pole barn, while a very large storage building, is covered with naturally weathered boards and exposed rafter tails that mimic other buildings on the property. The Workshop is one building that has been altered due to the growth of the manufacturing operation. However, many of the changes that have occurred to the building fall within the period of significance and were executed by Nakashima; therefore, the changes are similar to and fit in with the buildings on the property. The setting for the property includes many small landscape elements that add considerably to historic value of the property. These landscape elements include small ponds, scattered trees some of which are unique specimens to the area, clusters of boulders and stone walls. Overall the property retains all aspects of historic integrity including its location, setting, materials, design, workmanship, feeling and association.

8. STATEMENT OF SIGNIFICANCE

Certifying official has considered the significance of this property in relation to other properties:
Nationally: X Statewide:_ Locally:

Applicable National Register Criteria:	A_ B X C X D
Criteria Considerations (Exceptions):	A_ B_ C_ D_ E_ F_ G
NHL Criteria:	2 and 4
NHL Exceptions:	8
NHL Theme(s):	III. Expressing Cultural Values 5. architecture, landscape architecture, and urban design; 6. popular and traditional culture. V. Developing the American Economy 1. extraction and production 2. distribution and consumption
Areas of Significance:	Architecture Art (American Craft movement) Commerce Engineering Ethnic Heritage, Japanese Industry Landscape History
Period(s) of Significance:	1946-1982
Significant Dates:	
Significant Person(s):	George Nakashima
Cultural Affiliation:	
Architect/Builder:	George Nakashima
Historic Contexts:	XVI. Architecture International Style

State Significance of Property, and Justify Criteria, Criteria Considerations, and Areas and Periods of Significance Noted Above.

Introduction

The George Nakashima Woodworker complex is significant under NHL Criterion 2 for its association with internationally renowned furniture designer and woodworker George Nakashima, and under Criterion 4 for its innovative Japanese influenced International Style structures designed by Nakashima and built under his direct supervision. Criterion Exception 8 with regard to the fifty-year rule is applicable since six of the seventeen contributing resources on the property post-date 1963, although all but one was designed by Nakashima, who lived, worked, and played a role in the furniture business on the property until his death in 1990. These more recent buildings also played integral roles in the operation of the company and the relationship of his family, which were interwoven. The property includes his former residence, studios, showroom, production workshops, reception house, lumber storage buildings, and other resources associated with his family and career from 1946 through 1990. Construction began on the first building in 1946; the last building George Nakashima designed and built was completed in 1975. Mira Nakashima-Yarnall continues to produce furniture based on her father's archive of designs, as well as her own original work, which is in keeping with his design philosophy. She and other family members, including her brother Kevin and some of her children and their families are also involved in the business.

George Nakashima is recognized as one of America's most eminent furniture designer-craftsman, and a significant force within the American Craft movement of the mid-twentieth century, a seminal period for woodworking in the United States.[1] As a self-proclaimed "woodworker," Nakashima became an important voice for the artist craftsmen, helping to create a new paradigm for studio furniture production in the postwar period.[2] While revered as a master craftsman, Nakashima preferred the moniker "woodworker," reflecting his life-long commitment to the subjugation of the ego as a means to developing his creative force. Nakashima's exposure to eastern religion and Japanese craft traditions taught him not only the value of humility, but of seeking peace, beauty, and harmony through one's work. As was true with the previous Arts & Crafts period of furniture making, Nakashima and others within the new movement rejected the mass-production brought on by the machine age. At the same time, they embraced Modern stylistic influences and ideas that were international in scope. Reflecting the European Modernist tradition, Nakashima espoused a minimalist, utopian vision of design for the common man. Often defined as "organic naturalism," his timeless pieces defy stylistic categorization, although some designs harken back to American classics such as the Windsor chair and the Shaker "plain style."[3] Believing in the spiritual qualities of wood, Nakashima's signature features incorporated techniques intended to enhance the impact of the wood's natural beauty, such as the "free-edge" and the use of butterfly inlays. The wood was cut along the grain to form large, monolithic slabs and elements generally viewed as imperfections such as knots and splits were celebrated. Nakashima's veneration for wood as his

[1] David L. Barquist, "Druids and Dropouts: Working Wood, 1945-1969," in *Crafting Modernism: Midcentury American Art and Design,* ed. Jean Falino (New York: Abrams, in association with Museum of Arts and Design, 2012), 226-245.

[2] Janet Koplos and Bruce Metcalf, *A History of American Studio Craft* (Chapel Hill: The University of North Carolina Press, 2010), 249-250. According to the authors, Nakashima received quite a bit of publicity and his opinions became influential. He and a few others represent a new paradigm for studio furniture: the woodworker. As they explained, Nakashima defined woodworker as "one who makes things in wood, adopting an approach that seeks to integrate both art and craft," taken from George Nakashima, *Soul of a Tree*, 219. Nakashima outlined his "woodworker" philosophy is his address at a path-breaking conference held in New York in 1953 on the topic of the influence of design on modern living.

[3] Steven Beyer, *George Nakashima and the Modernist Moment* (Doylestown, Pennsylvania: James A. Michener Art Museum, 2001), 12. Nakashima's designs for chairs in particular are reminiscent of traditional American designs such as the Windsor chair or chairs crafted by Shaker craftsmen.

medium is expressed in his seminal work *The Soul of a Tree,* where he speaks of his desire to "offer the tree a second life of dignity and strength." The book has provided inspiration for many craftsmen.[4]

His success as an artisan propelled him briefly into the arena of mass-production; between 1945 and 1954 internationally recognized modern furniture manufacturers Hans and Florence Knoll produced a selection of Nakashima's designs, which appeared alongside other noted modernists including: Franco Albini, Harry Bertoia, Pierre Jeanneret, Ludwig Mies van der Rohe, Isamu Noguchi, Eero Saarinen, and Florence Knoll herself. High-end furniture manufacturer Widdicomb-Mueller of Grand Rapids, Michigan likewise produced suites of Nakashima furniture, between 1957 and 1961. According to Steven Beyer, "By the early 1950s, less than ten years after the establishment of his studio, Nakashima had distinguished himself as one of the most important [furniture] designers practicing in America." His foray into mass-production exposed Nakashima to a much broader audience, elevating his national standing as a designer and leading to comparisons with other noted American furniture designers of the era such as Charles & Ray Eames. However, Nakashima saw furniture making more as a spiritual journey, crafting unique pieces that responded to the natural form of each piece of wood.[5] Thus he soon returned to his workshops as his sole means of production and, with the help of a handful of skilled individuals (which later included daughter Mira), was able to maintain his high standards for quality and integrity. In this regard, Nakashima is more appropriately compared with prominent craftsman such as Wharton Esherick and Sam Maloof. Still, Nakashima's work expresses a worldview that is based upon a unique set of circumstances including his formal education in architecture, his exposure to European Modernism, eastern religious philosophy, and traditional Japanese craft traditions, including instruction from Issei carpenter Gentaro Hikogawa while both men were confined in a Japanese-American Internment Camp. As a testimony to George Nakashima's skill and national prominence, he was awarded the American Institute of Architect's Craftsmanship Medal in 1952. Nakashima's work has also been included in some of the most celebrated national exhibitions of handcrafted Modern furniture of the twentieth century, and he appears in every noted publication on the craft movement and fine woodworking in America.[6]

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[4] George Nakashima, "The Soul of a Tree," in *The Craft Reader,* ed. Glenn Adamson (Oxford and New York: Berg Publishers, 2010), 222. Originally published as George Nakashima, *The Soul of a Tree: A Master Woodworker's Reflections* (Tokyo/New York: Kodansha, 1981).

[5] Todd Merrill and Julie V. Lovine, *Modern Americana: Studio Furniture from High Craft to High Glam* (New York: Rizzoli International Publications, Inc., 2008), 125. According to the authors, "George Nakashima was surely one of the most recognized of the so-called studio furniture makers emerging from the postwar period. His name was constantly linked with the likes of Charles Eames and Eero Saarinen. However, while those designers were dedicated to the cause of mass production, Nakashima remained adamantly a craftsman, ever suspicious of the dehumanizing effects of the machine made."

[6] Exhibits include: the Museum of Modern Art's first exhibition of American design titled, *Design for Use, USA* (1951); the Renwick Gallery of the Smithsonian Institution's *Woodenworks* (1972); and Boston's Museum of Fine Arts's *The Maker's Hand: American Studio Furniture, 1940-1990* (2003). Nakashima's work has also been the focus of exclusive showings, such as: New York's American Craft Museum's *Full Circle*, a fifty year retrospective (1989) and the James A. Michener Museum's *George Nakashima and the Modernist Moment* (2001).

Publications in which George Nakashima is the sole subject include: and Derek E. Ostergard, *George Nakashima: Full Circle* (1989); Steven Beyer, *George Nakashima and the Modernist Moment* (2001); Mira Nakashima, *Nature, Form & Spirit: The Life and Legacy of George Nakashima* (2003). He was also included in an influential study organized by the Committee on Design and Craftsmanship titled "A Study of Design and Craftsmanship in Today's Products" presented by the Walker Art Center in Minneapolis, which included an exhibition and conference. George Nakashima is featured in the most authoritative texts on American craft, Modernism, and studio furniture, including: Edward S. Cook et al, *The Maker's Hand: American Studio Furniture, 1940-1990*; Glenn Adamson, ed., *The Craft Reader* (2010), the first comprehensive anthology of writings on modern craft; Todd Merrill and Julie V. Lovine, *Modern Americana: Studio Furniture from High Craft to High Glam* (2008); Jeannine Falino and Jennifer Scanlan, *Crafting Modernism: Midcentury American Art and Design* (2011), in-depth examination of the American studio craft movement in the decades following World War II (featuring the greatest artisans within the major mediums); Janet Koplos and Bruce Metcalf, *A History of American Studio Craft* (2010). The Woodenworks exhibition was also accompanied by a publication: *Woodenworks; Furniture Objects by Five Contemporary Craftsmen: George Nakashima, Sam Maloof, Wharton Esherick, Arthur*

George Nakashima began his professional career as an architect, working at the vanguard of International Modernism in Japan before turning to furniture design. Thus as a trained architect, George Nakashima is also responsible for the design and construction of the structures that comprise the Nakashima Woodworker complex, erected between 1946 and 1982. Designed in the International Style intermingled with elements of traditional Japanese architecture and featuring the innovative use of concrete, these structures are to be considered among the treasures of Nakashima's unique legacy of craftsmanship. Pure examples of the International Style are fairly rare, and these structures reflect Nakashima's exposure to some of the early pioneers of the style that gave birth to the Modern movement in architecture. Most notably, Nakashima worked in Japan with Antonin Raymond who was a protégé of Frank Lloyd Wright and is generally considered to be a father of Modern architecture in Japan.[7] While Nakashima's skillful and innovative approach to architecture is manifested in the buildings that he designed for his New Hope complex, examples of his work in the United States are extremely limited. In fact, his transformation from architect to furniture designer was primarily a reaction to American architectural practice in the mid-twentieth century, which he found antithetical to his earlier experiences in Europe and Asia. Nakashima embraced the hallmarks of the new International Style, such as its simple forms and clean lines, open plan, and expansive glass—elements often made possible through the plasticity of concrete construction. To this he added authentic elements of traditional Japanese building craft. In addition, well known structural engineers Paul Weidlinger, Matthys Levy and Mario Salvadori worked with George Nakashima on the Conoid Studio, Chair Department, and the (first) lumber storage building to create unique, experimental roof forms using concrete construction.

George Nakashima's Early History and Influences

George Nakashima was born May 24, 1905 in Spokane, Washington. He grew up in the forested mountains of the Pacific Northwest that surrounded his family home in Seattle. His education consisted of the study of forestry—perhaps initiating his reverence for trees—and then architecture at the University of Washington. In 1928 he was given a one-year scholarship to study architecture in Paris at the Ecole Americaine des Beaux-Arts in Fountainebleu. After graduating from the University of Washington in 1929 he received a scholarship to attend the Graduate School of Design at Harvard University. Preferring a better grounding in engineering, he soon transferred to the Massachusetts Institute of Technology (MIT) and received a Masters degree in architecture in 1930. While Nakashima believed that architecture must transcend engineering, he felt that an understanding of engineering principles and the nature of building materials was essential in order "to satisfy an architect's obligation to truth."[8] After MIT he was hired by the Richard Brooks Studio in New York to paint

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Espenet Carpenter, Wendell Castle (1972). George Nakashima was the cover feature in *Fine Woodworking* magazine, a publication considered to be the first comprehensive periodical for technical information on hand skills, new technologies, machine tools, and woods. See: John Kelsey, "George Nakashima: For Each Plank There's One Perfect Use," *Fine Woodworking* 14 (Jan.-Feb. 1979): 40-46.

George Nakashima's house has also been featured in three publications: Tina Skinner, *Esherick, Maloof, and Nakashima: Homes of the Master Wood Artisans* (2009); and Leslie Williamson, *Handcrafted Modern: At Home with Mid-century Designers* (2010), which includes the most significant interiors created by the designers themselves as their own residence, including those of: Russel Wright, George Nakashima, Harry Bertoia, Charles and Ray Eames, Walter Gropius, Eva Zeisel, and Albert Frey; Michael Gotkin, *Artist's Handmade Houses* (2011), featuring the homes of Henry Chapman Mercer, Paolo Soleri, Russel Wright, Henry V. Poor, Raoul Hague, George Nakashima, Ralph R. Whitehead and Jane B. McCall, Sam Maloof, Frederick E. Church, Constantino and Ruth Nivola, Ruth and Robert Hatch, and Michael Kahn and Leda Livant.

[7] Kurt G. F. Helfrich and William Whitaker, eds., *Crafting a Modern World: The Architecture and Design of Antonin and Noemi Raymond* (New York: Princeton Architectural Press, 2006), 25.

According to Mira Nakashima, at Harvard, "he soon discovered that Harvard's program was based on the theoretical design approach of Walter Gropius and the Bauhaus School. So, after only a few weeks at Harvard, his quest for a solid grounding in engineering propelled him to . . . MIT." Mira Nakashima. *Nature, Form & Spirit: the Life and Legacy of George Nakashima* (New York: Abrams, 2003), 13.

murals for the New York capitol building in Albany and a year later was hired by the Long Island State Park Commission to paint murals and design buildings. He worked on projects at Jones Beach, Sunken Meadow Park, and Montauk Point. He lost the job in 1933 due to the depression and traveled across the country to Seattle to see his parents. From Seattle he traveled back to New York and then via steamship across the Atlantic Ocean eventually making his way once again to Paris.

Near Nakashima's apartment in Paris, renowned Modernist architect Le Corbusier's "Pavillion Suisse" was under construction. According to his autobiography *The Soul of a Tree*, Nakashima made weekly visits to observe the process.[9] The Pavillion Suisse is considered a landmark Modern design. It signaled the application of the International Style to structures other than those intended for industrial purposes, moving beyond functionalism to incorporate curvilinear forms and aesthetic details. Nakashima was greatly impacted by this structure. According to Mira Nakashima,

> While Nakashima had surely been introduced to the design philosophy of Le Corbusier during his years of studying architecture in the United States and at Fontainebleau, seeing the Pavillion being built allowed him to observe the Swiss master's work at very close hand. As he watched the structure grow week by week, he was filled with excitement to learn Le Corbusier's techniques and methods of building, his innovative use of concrete, and his new forms. Nakashima's vigilant observation allowed him to carry an intimate knowledge of the procedure and construction methods of reinforced concrete—not to mention a love for the expanded possibilities of the medium—throughout his life.[10]

Nakashima appreciated, and later applied to his own designs in New Hope, Le Corbusier's use of concrete, open-space planning, simple, clean lines, and horizontal courses of windows (intended to admit as much light as possible). Le Corbusier also calibrated his proportions based on the height of a man, which, he believed, assured a sense of harmony throughout the work, and promoted a feeling of peace and well-being. According to Mira, "All of these principles were, in fact, shared by the traditional architecture of Japan, and they resonated deeply with Nakashima."[11]

After a year in Paris, Nakashima traveled to Japan. He visited his mother's ancestral home in Kamata and was immersed for the first time in the traditional lifestyle of the Japanese. As Nakashima described his time in Japan, "It was a great experience to savor the life of my forebears after having spent my youth in America. The sensitive environment, the expressive language, the excellence of the architecture and crafts, the traditions and the personal relationships—all touched me to the depths of my being."[12] In 1934 he took a job with architect Antonin Raymond, who is recognized as the father of Modern architecture in Japan.[13] Raymond came to Japan to work with Frank Lloyd Wright on the Imperial Hotel, and decided to stay and set up an architectural office in Tokyo after the project was completed. Raymond was interested in integrating modern Western building technology with traditional Japanese architectural forms. In so doing, he worked closely with Japanese craftsmen and absorbed their traditions in a manner that had apparently eluded Wright. Likely as part of their personal interest and professional study of Japanese building traditions, Nakashima traveled with coworker Junzo Yoshimura to visit various architectural monuments, including the shrines and temples of the ancient capital of Kyoto. According to Nakashima, these were "fabulously built wooden structures expressing the

[9] George Nakashima, *The Soul of a Tree: A Woodworker's Reflections* (New York: Kodansha International, 1981), 10.
[10] Mira Nakashima, *Nature, Form & Spirit*, 16-17.
[11] Ibid., 18.
[12] George Nakashima, *Soul of a Tree*, 59.
[13] Helfrich and Whitaker, *Crafting a Modern World*, 25.

beauty and serene quality of the island people of Japan, and the deep reverence these people have for nature."[14] They also attended tea ceremonies and festivals. The cumulative effect of these experiences was the development within Nakashima of a deep appreciation of Japanese cultural and architectural traditions. In addition, Sakakura and their other coworker, Kunio Maekawa, had worked with Le Corbusier in Paris and so Nakashima was able to learn more about the master's work and to exchange ideas.[15]

Around 1936 the Raymond office received a commission to design a building for the ashram of Sri Aurobindo in Pondicherry, India. George Nakashima was interested in working in India and agreed to oversee the design and construction of the building. While working on the project, he became a disciple of Sri Aurobindo and partner Mira Alfassa, and donated his salary for the project to the monastery. They had developed a spiritual philosophy known as Integral Yoga, which taught that beauty is the expression of divine truth, that freedom fosters creativity, and that focus develops discipline. These ideas deeply affected Nakashima such that "when he established his own studio in Bucks County, he wanted it to be a center for the evolution of a life moved by a higher consciousness, a life of the spirit." Thus according to his daughter Mira, "He always spoke of his work as a spiritual adventure, as an attempt to bring forward his psychic being, but rejecting all that comes from the ego, vital desire, and the mind's presumptuous, reasoning incompetence."[16] The building, named Golconde, was constructed in the International style of reinforced concrete with a roof made of 5' x 3' pre-cast concrete barrel vaulted sections. The experience underpinned Nakashima's passion for, and increased his knowledge of, reinforced concrete construction that he would later realize in his designs for the New Hope compound.

George Nakashima completed his work in India and traveled back to Tokyo in 1939. At this time the world was on the verge of war and Antonin Raymond closed his office in Tokyo and moved to New York City, later purchasing a farm outside of New Hope, Pennsylvania. While he was in Tokyo George Nakashima met Marion Okajima, a Japanese American working as a private English tutor, and they were engaged. When he returned to the United States, Marion joined him and they were married in Los Angeles in 1941. Settling in Seattle, Nakashima worked as an architect for Ray Morin while beginning to make furniture part time. Father Leopold Tibesar of the Maryknoll Boy's Club gave Nakashima permission to use their basement workshop in exchange for teaching the boys woodworking. He set up a small furniture shop and it was there that he produced his first privately commissioned collection of handcrafted furniture, for cosmetics executive Andre Ligne. The commission allowed Nakashima to devote himself full-time to furniture making and he made the decision to reject his architecture career. He had become increasingly disillusioned by American architectural design and practice, particularly that of Frank Lloyd Wright, whose work, although beautifully designed and spectacularly celebrated, was poorly engineered. Nakashima believed, however, that furniture making was a natural extension of architecture at a smaller scale, and that his experience as an architect could inform his furniture design. While in Seattle, he also developed a friendship with artist Morris Graves who shared his interest in Indian philosophy and who gave him a book on Shaker furniture, a now well-worn volume within his still extant reference library.

On December 7, 1941 the Japanese attacked Pearl Harbor and shortly thereafter those of Japanese ancestry living on the West Coast were forced into internment camps away from the Pacific Coast. The Nakashimas, including their newborn daughter Mira, were relocated to Camp Minidoka in Idaho. In George Nakashima's autobiography *The Soul of a Tree,* he describes the mass incarceration in the internment camps as "a stupid and insensitive act, one by which my country could only hurt itself. It was a policy of unthinking racism."[17]

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[14] George Nakashima, *Soul of a Tree*, 58.
[15] Mira Nakashima, *Nature, Form & Spirit*, 18.
[16] Ibid., 34.
[17] George Nakashima, *Soul of a Tree*, 69.

Despite the horrendous circumstances, Nakashima made the best of his situation. As luck would have it, Japanese carpenter Gentaro Hikogawa was also incarcerated at the camp; Hikogawa was well trained in the use of traditional Japanese hand tools and had an intimate knowledge of Japanese wood joinery. Hikogawa taught his skills to Nakashima, thus enhancing Nakashima's already considerable furniture making ability. They used scraps of wood and bitter-brush scavenged from the desert to make pieces of furniture that could enhance their primitive living conditions. While Nakashima claimed to bear no scars from the interment experience, it certainly strengthened his beliefs. As Mira explains, "Fortunately, he was able to transform anger and negativity into the positive passion of conviction, the passionate creativity of his work, and the passion for beauty and perfection, which served him well."[18] Rather than building animosity because of his heritage, Mira points out that "My father's insistence that he was a citizen of the world not limited by national or racial boundaries, enabled him to rise above prejudice and persecution, to embrace, rather than reject the Japanese culture and aesthetics as few, if any, of his fellow internees dared."[19] In fact, the experience eventually led to the conception of the globe-encircling Altars for Peace that he would erect in his later years.

In 1943, one of George Nakashima's professors at MIT contacted his former employer Antonin Raymond to petition for the release of the Nakashima family which was granted with the provision that Nakashima work for Raymond. Since many of Antonin Raymond's jobs at the time were government related, Nakashima could not work as an architect, but as a worker on his New Hope farm, primarily tending to the chickens. However, he was able to set up a small workshop in the Raymond's milk house, designing what became known as the "milk house" stool and table, which, among other designs, were a regular part of his furniture line. While living in the New Hope area, George Nakashima also became enamored with the building traditions of the early Quaker settlers. In fact, in *The Soul of a Tree*, he includes sketches of the nearby Thompson-Neely house and barn.[20] In 1945, after the war was over, George Nakashima moved into a small house near Meetinghouse Road and continued to design and build furniture. In 1946, he approached a Quaker farmer and asked him if he could have three acres of his land along Aquetong Road in exchange for carpentry work. The farmer agreed and George Nakashima began to construct his Workshop while he and his family lived in a tent on the property. The parcel was expanded through the years to 8.7367 acres, 12.2 acres including Mira's property.

The Development of the George Nakashima Woodworker Complex

Soon after he acquired the land George Nakashima built his Workshop, immediately followed by the design and construction of a house for himself and his family. Thus began a tradition of combining family residential buildings with workshops, storage buildings, and studios; and mixing family life with the manufacture, design, and marketing of furniture. As the business grew Nakashima hired workers to assist him, who often became like family members themselves. George Nakashima was the creative talent, while his wife Marion acted as the business manager. Children Mira and Kevin Nakashima would eventually become a part of the business, with Mira playing a major role in the design and manufacturing of the furniture, including the execution of designs from the archive left by her father as well as the introduction of her own design in the same spirit. The house the family lived in was small, just one story high and relatively simple in design, reflecting his signature blend of Modern architecture and Japanese building traditions. In addition to designing these buildings, George Nakashima also took a hands-on approach to their actual construction. He was his own general contractor on each project and directly supervised the work, if not actually performing the work himself. He also rarely made blue prints of his designs. Instead he drew his plans by hand with pencil on paper, which was also true of his furniture designs. Although Nakashima was capable of producing high-quality architectural renderings, the fact

[18] Mira Nakashima, *Nature, Form & Spirit*, 43.
[19] Ibid., 41.
[20] George Nakashima, *Soul of a Tree*, 69, 71.

that none were produced for these structures reflects Nakashima's insistence on being an active participant in the construction as well as the design process.

The first structure to be erected was the Workshop, in 1946. It is a simply constructed building made of cement block with large windows in the southern exposure for natural lighting and war surplus Transite roofing. It has been expanded over the years to include additions made in 1959, 1970, and 1988. While the Workshop is an unassuming structure, it has been in continuous use as the site for the production of Nakashima furniture since its inception in 1946. It is where most of the furniture was created, the woodworkers trained, and where Nakashima worked through the creative process to realize new designs.

George Nakashima next turned to building a house, which he did largely on his own using both traditional and/or indigenous and experimental materials. According to daughter Mira,

> The house was of stone, with oak framing, and some experimental materials such as concrete roof tiles. I remember watching my father hand-pouring and setting the concrete tiles on the roof, and we used to pick up fieldstone along the highway and put them in the car if they looked to be the right size and shape for the wall he was constructing. Dad would often send me to the rock-pile to find small stones to fit into a particular spot; it was my first lesson in architecture.[21]

In the tradition of the International Style, the George Nakashima House combines natural materials including local stone, white stucco walls, and simple wood trim to create an asymmetrical design that also features exposed framing, ribbon windows, glass walls in the living area, and an open floor plan. Elements indicative of Japanese architecture include rice paper Shoji screens used as dividers, and rafters and support posts (or parent posts) consisting of un-milled trees simply stripped of their bark. The living room ceiling is made of wide cedar panels held by clips to allow for expansion. The alternating use of materials, the lack of symmetry, and exposed structural elements create architectural interest, the result of which is that no two elevations resemble one another. The street front features local stone with an entrance almost hidden in a recessed area to one end. In the opposing elevation, the stone is carried out in the retaining wall while the section of wall above is faced in stucco. One end of the house is covered with natural wood planks laid vertically while the other is of plain stucco. As with all the Nakashima structures, the attention to detail is striking. Dark stained rafters extend under the eaves and in the gable ends, with the rafter ends painted white to highlight them; similar exposed framing appears in the ceiling of the recessed entry porch, and various structural elements appear on the exterior where the roof supports meet the walls. And as in the Japanese tradition whereby houses are to be in harmony with nature, transition between the indoors and outdoors is created by means of wide doorways entering onto patios and decks. There is no railing on the deck to obstruct the view and large stones are used as they were found in nature as steps leading from the deck to the yard, which is covered in pebble-sized stone. Stone retaining walls help to level the house and yard, which is banked within the hillside.

For a considerable length of time (1946 to 1954) the Workshop and house were the only buildings on the property. A series of events occurring during this period greatly increased Nakashima's recognition, providing both the demand and capital needed to expand his business. The result was the design and construction of additional structures to the new Hope complex. In 1946 Nakashima established a relationship with H.G. Knoll Associates, a furniture manufacturer in New York City, and with Widdicomb-Mueller Company of Grand Rapids, Michigan, in 1957. While short-lived, these relationships presented significant opportunities for Nakashima. In 1951 examples of George Nakashima's furniture were included in a well traveled, ground-

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[21] Mira Nakashima, *Nature, Form & Spirit*, 46.

breaking exhibition of Modern design initiated by the Museum of Modern Art in New York City. From 1951 to 1961, the Jamaican resort, Frenchman's Cove, commissioned George Nakashima to build a collection of furniture for the resort. Two dining tables designed for the Frenchman's Cove project became part of Nakashima's regular line of furniture and were sold at after 1958 at the new Showroom.

In 1955 a building was constructed for lumber storage, which was quickly converted to a furniture Finishing Department. Thus began a significant period of construction at the New Hope property. Mira describes her father's work during this period:

> As the furniture business prospered, it afforded him the financial capability to consider building again, and indeed, demanded more space for his operations. He also continued to design and build elsewhere as opportunities arose. Although he had not done any architectural work since he had put up his first house and workshop on the New Hope property, 1954 marked the beginning of a flurry of building, which would include new space to work, to show pieces to clients, and to store the expanding inventory of lumber, and even in 1960, to build a kidney-shaped swimming pool and barrel-vaulted pool house. The most important of these new buildings was the Conoid Studio, which would be a combination design studio, conference room, and a place to keep some of his finest pieces of wood.[22]

Along with the Finishing Department, George Nakashima designed and built the Showroom in 1954. Like the Nakashima house, the Showroom is a finely crafted structure that blends inside with out, and Modernism with traditional Japanese motifs. It is a one-story rectangular building with a large open interior space to display furniture, with ample room for conducting business. Also like the Nakashima house, it includes character defining elements such as exposed framing members highlighted against white drywall ceilings, stone walls visible both inside and out and including a stone fireplace with custom-designed metal hood, large expanses of glass, and the use of shoji screens. Again, in keeping with the Japanese philosophy of harmonizing the structure with its natural environment, sliding glass doors lead to a wood deck that overlooks a small pond, situated at the gable end. The surrounding landscape includes stone retaining walls and pebble walks.

In 1954, Kevin Nakashima was also born to George and Marion Nakashima. As a result, the house had to be expanded by an addition to include another bedroom.

Building continued on the property and by 1956 George Nakashima began the use of experimental warped shell roof designs, particularly the conoidal and hyperbolic paraboloid. Simplistically speaking, a conoid is a modified cone shape, while a hyperbolic paraboloid is a saddle-shaped curve. Both are innovative and economical methods of covering a large area with a relatively thin and lightweight roof surface. In experimenting with the conoid shell roof type, Nakashima designed and built a clubhouse or lounge for his workers in 1956. The building's roof was made of a layered plywood shell. The clubhouse was soon converted for use as a chair assembly shop, or the Chair Department as it is now known. It was followed in 1960 with the construction of the most remarkably engineered and designed building on the property, the Conoid Studio. To construct the Chair Department (1957), Conoid Studio (1957-60) and the main lumber storage building (1956) George Nakashima hired engineers Paul Weidlinger, Mario Salvadori, and Matthys Levy of Weidlinger Associates. Paul Weidlinger was the founder of Weidlinger Associates Incorporated in New York City, which

[22] Ibid., 136.

continues to be one of the most outstanding engineering consulting firms in the world, specializing in the analysis and effect of seismic activity on buildings and structures.[23] As Mira explains,

> During the 1950s he [George Nakashima] became fascinated by the capabilities of warped thin-shell or "form-resistant" structures. He especially admired the work of Mario Salvadori, Paulo Luigi Nervi, and Felix Candela, and had a correspondingly low opinion of some of Eero Saarinen's concrete structures, which he called 'unwilling' shells, because of their thickness. He determined to build his own shells, based on sound engineering principles that would permit both an economical use of materials and 'organic' forms. Behind this idea lay a belief that sound engineering was an expression of the laws of nature, and that a beautiful structure was a manifestation of those laws.[24]

The studio measures 40' x 40' and so the idea of the curved or conoid shape was to support the roof and allow it to cover a large open space. While an ordinary conoid has a doubly curved surface, the team decided to add a series of small sine curves to increase the strength of the roof, resulting in its unusual scallop-shell-like appearance. The roof is supported and further strengthened by a reinforced concrete arch located at the overhanging front of the building, with a concrete lintel atop the wall supporting the rear and stiffeners inserted in alternate corrugations. According to an article appearing in *Engineering* magazine at the time of its construction, "The resulting shell has an entirely new form and represents a new application of the conoidal shell." As the article also states, while conoidal shells are frequently used in monitored industrial buildings in Europe, they are rare in the United States. Thus, this represents a "departure in the design philosophy of reinforced concrete shells"[25] and a truly unique structure. The roof of the Conoid Studio is not only unique for its shape, but also for its poured reinforced concrete construction, which measures only 2-½" in thickness.

The interior of the Conoid Studio is a masterful blend of Modern design with Japanese elements such as shoji screens to modulate the light emanating from the completely glazed front wall. The conoid roof was highly successful in creating the desired effect. As Mira describes it:

> The overall effect of the interior of the Conoid Studio is that of a soaring, freely undulating, but organically disciplined space, something like a gigantic, organically formed seashell, transiting in graduated waves from a flat sine curve to an open arch facing the sun. The walls of this structure would be largely glass, as they did not have to carry the weight of the roof.[26]

A finely crafted wood partition separates the studio space from the domestic uses, such as the kitchen, bathroom, storage, and design office space.

Interleaved with George Nakashima's building and architectural work on his New Hope property, the furniture manufacturing business was thriving. Construction of the Conoid Studio inspired George Nakashima to design

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[23] Mario Salvadori was an engineer and architect who worked on the Manhattan Project during World War II. In 1956, Matthys Levy was a recent graduate in structural engineering from Columbia University. He went on to design and engineer landmark structures including the Georgia Dome in Atlanta and La Plata Stadium in Argentina. He also was a consulting engineer on the investigation into the collapse of the World Trade Center buildings in New York City on September 11, 2001. He currently is chairman of Weidlinger and Associates, Inc. in New York City.

[24] Mira Nakashima, *Nature, Form & Spirit*, 136.

[25] "Adventure in Structure, Sea Shell Roof," *Architectural Record* 122 (November 1957); and Matthys P. Levy and Paul Weidlinger, "Conoid with Corrugations Makes an Unusual Roof," *Engineering News-Record* 159 (December 5, 1957).

[26] Mira Nakashima, *Nature, Form & Spirit*, 136.

an entire line of furniture that he sold at his New Hope showroom including the Conoid chair, bench, coffee table, end tables, and dining table. The Conoid furniture differed from much of Nakashima's earlier work by including daring architectural elements such as "rigorously architectonic bases" cantilevered seats, angled back supports, and thin floor runners. As biographer Derek Ostergard points out, Nakashima used for the first time the "fully developed cantilevered seat, a powerful statement, perhaps reflecting confidence after completion of the Conoid Studio."[27]

Like the Arts Building, the main lumber storage building constructed in 1956 of cement block has two thin hyperbolic paraboloid roofs built with three layers of 3/8" plywood in order to cover a large open space of thirty-one square feet. Noted for its economy and ease of construction, Nakashima called his new method of constructing a hyperbolic paraboloid, "perhaps the easiest and cheapest way to roof a clear span of this size."[28]

In 1958, George Nakashima was commissioned to design an outdoor living room by the Simpson Lumber Company of Arcata, CA. The living space was designed as a cantilevered lean-to anchored in a concrete base and included a stone barbecue. The "Lanai," as it came to be known, was designed to be built of redwood. The lumber company advertised the outdoor family room in various popular magazines of the time, offering copies of the plans for the structure at no charge. This was a marketing tool by the Simpson Lumber Company to entice customers to purchase its redwood lumber products. In the July 1958 issue of *The Woodworker* Nakashima is quoted as saying the project was intended to "bring the East to the West." As it was explained, "This 'lanai' features two cantilevered piers of reinforced concrete around which Nakashima has used California redwood to produce an aura of pure beauty as well as practicality. The graceful shingled roof imparts a light and serene feeling and the entire structure is airy, yet strong; protective, yet unobtrusive, and the design reflects the manner in which wood can be worked with the best styling of both the Orient and the West."[29] The prototype for the Lanai is on the Nakashima property near the Reception House, and includes a stone beehive barbecue.

In 1959, the small and somewhat inconspicuous Pool Storage House was constructed. Its significance is that it was a prototype for the much larger Pool House that was built nearby in 1960. Mira Nakashima, a high school senior at the time, assisted with the design and construction of the Pool Storage House. Both the pool storage building and the Pool House have plywood barrel vaulted roofs set on solid stone or cement block foundations. The Pool House was also designed to have a passive solar heating system that provides hot water for showers in the building. The Swimming Pool is also uniquely designed and engineered with a cantilevered concrete extension on the south side and won a design award in 1960.

By now, the Nakashima complex had grown considerably and in a manner that was well integrated with the natural environment. In his furniture catalog Nakashima described himself as an architect for the whole environment, able to produce "an integrated concept of architecture, furnishings and landscape."[30]

The next building to be constructed on the property was the Arts Building, in 1967. The building has a hyperbolic paraboloid roof design and was specifically constructed to display the works of Ben Shahn, the well-known mural painter, photographer, and social activist. George Nakashima and Ben Shahn became friends in the 1950s. George Nakashima designed an addition on Ben Shahn's house in the New Deal community of

[27] Derek E. Ostergard, *George Nakashima: Full Circle* (New York: Wiedenfeld & Nicolson, 1989), 77.
[28] "A Lumber Storehouse, New Hope, Pennsylvania," *Architectural Record* 126 (July 1959).
[29] Kenneth R. McDonald, "Pennsylvania Designer Uses California Redwood to Fashion this 'Lanai'," *The Woodworker* (July 1958): 31.
[30] Ostergard, *George Nakashima*, 80.

Roosevelt, New Jersey, and Ben Shahn purchased furniture from George Nakashima. From 1967 to 1969, Ben Shahn's art was sold at the Nakashima studio in New Hope and in the Arts Building following its construction. Ben Shahn sketched a tile mosaic that he proposed for installation on the west wall of the Arts Building. Unfortunately Shahn passed away in 1969, prior to its execution by the Gabriel Loire stained glass studio in France. The tile mosaic was built in eight sections and transported back to New Hope for installation on the west wall in 1972. Among the extraordinary features of the Arts Building is its cantilevered stairway, handcrafted by Nakashima, with steps resembling the edges of the milk house table embedded into the stone wall; its soaring roofline with exposed beams, its open space interior, and expansive glass walls. Perpendicular to the Arts Building is "the Cloister," a series of rooms—bedroom, bathroom, and service kitchen—that Nakashima intended to house visiting craftsmen from Japan (although that goal was never realized).

In 1970 Nakashima's daughter Mira and her family were in need of a place to live in the New Hope area and so he purchased a parcel of land across Aquetong Road from the main complex in 1968 and began the construction of her house. In the design and construction of Mira's house and an adjacent guesthouse, he employed a scissors truss roof, which is basically an asymmetrical gable resembling a partially open pair of scissors. It is an economical means of supporting a roof that with the addition of natural tree support posts on the interior and exposed support structure makes the roof both aesthetically pleasing and well engineered. It shares many of the same qualities of the George Nakashima House in its styling, use of materials and architectural elements, and blending of indoors and outdoors. It combines stucco and wood with concrete block, and has an open plan with sliding doors that lead out to a deck. The site also includes a small guesthouse of the same materials and also has the character defining scissor-truss roof.

Another building on the property that employs the use of a scissors truss roof is the Reception House or "Sanso Villa." Built in 1975-77, it was the last building on the complex to be designed and built by George Nakashima and is arguably his finest example of freely translated traditional Japanese domestic architecture. In addition to its demure scale and simplicity, it includes many other modern translations of defining characteristics of Japanese domestic architecture, including: its open space; exposed structural elements; three *nakabashira*, or internal posts, and a *daikokubashira*, also referred to as *oyabashira*, a parent or mother post; glass walls; *tatami* mat covered floors; and *shoji* screens. It begins with the *genkan* or welcoming entrance with storage for shoes, behind which is located a modern version of a *mizuya* or small kitchen with a cupboard and wash-up for tea utensils. The kitchen can be hidden behind shoji screens that open on to the dining area. On the other side of the room is the living area with a stone fireplace and built-in features including a window seat, *ji-bukuro* or low storage compartment (actually a casing for the heating elements) with cabinets above, and a *tsuke shoin* or built-in desk. The most distinguishing features are perhaps the attached Japanese tearoom, entered through an expanded *nijuri guchi* or a small doorway through which guests must enter on their hands and knees, and the *horiburo*, a sunken tiled but heated by convection from a Japanese wood-burning boiler.

The Reception House is furnished with many of Nakashima's signature pieces to complete the integrity of its design and jewel-box-like perfection. Like the other residential structures, the Reception House has sliding glass doors and a deck that looks out over the hillside from its terraced site. It reflects Nakashima's whole environment approach; the integration of architecture, furnishings, and landscape. With the completion of the Reception House in 1977, major architectural design and engineering work by George Nakashima on the site essentially, although he remained involved in the furniture design business continued until his death in 1990.

The International Style and Traditional Japanese Architectural Forms

As outlined, the structures that comprise the Nakashima complex were designed by George Nakashima in the International Style intermingled with elements of traditional Japanese architecture. While the combination may sound peculiar at first blush, as Nakashima has proven, the two are eminently compatible. Both styles seek simplicity of form, celebration of the natural beauty of the materials, and the conspicuous display of structural components. As already discussed, Nakashima's background provided him with a very distinctive set of ideas and experiences brought together to create this site. These experiences included his architectural education, personal observations on the work of Modernist master LeCorbusier, his own work in Japan and India for Antonin Raymond, eastern religious philosophy, and his exposure to traditional Japanese craftsmanship. Although Nakashima eventually abandoned architectural practice in favor of woodworking, he continued to design and build structures for his business and for himself and his family, and to bring an architect's understanding to the production of furniture. His keen perception of the philosophical and design principles that underpin both the International Style and traditional Japanese building practices are uniquely and expertly manifested at the Nakashima complex.

The International style first emerged in Europe in the 1920s and 1930s, and was formally introduced to America through a 1932 exhibition held at the Museum of Modern Art (MoMA). In a 1963 publication Henry Russell Hitchcock, one of the very same individuals responsible for that exhibition, announced that the International Style was now over.[31] The style had been deemed by many to be stark, cold, and elitist. And when compared to the revival styles of architecture then popular in the United States, perhaps their assessments were correct. The International style has always been considered a radical diversion from popular architectural practice, and in that regard it has been imminently successful; what early proponents of the International Style indeed intended was a break from the architectural conventions of the past. While pure examples of the International Style, particularly for residential architecture, are fairly rare, many mid-century Modern buildings reflect its influence. This is true most specifically with regard to the utilization of a set of basic design principles (outlined below) and the introduction of open floor plans.

Rather than slavishly copying the architectural styles of the bygone eras with all its fussy ornament, the International style sought beauty in the true character of construction. This notion has been popularly summarized by adages such as "less is more" and "form follows function." The three defining principles of the International Style—volume, regularity (rather than symmetry), and the avoidance of applied decoration—certainly reflect these ideals. If in fact the International Style is dead, it is certainly not forgotten, owing to the tremendous impact that it had on the profession worldwide. Before it was so named, the International style marked the emergence in Europe of the Modernist movement. It was nothing short of a revolution in architectural design that would reverberate across the globe. As one architectural historian explains, "The International Style served a vital purpose. By establishing a pattern and a method this movement provided the necessary backbone of the development of a new architecture, which might otherwise have floundered without certain shape or purpose. The International Style consciously defined a formula by which any architect could design a good building."[32] Thus the emergence of the International Style and the subsequent rejection of historical precedent in architectural design had a profound effect on architectural practice and education in the United States that continues to the present day.

The term "International Style" was coined by three individuals, Henry Russell Hitchcock, Phillip Johnson, and Albert H. Barr, Jr., who worked together in 1932 to create the MoMA exhibition of this emergent, largely European style in order to provide its U.S. début. Barr was the first director of MoMA; Johnson, an architect by training, was the founder of the museum's Department of Architecture and Design; and Hitchcock, a respected architectural historian. While attendance to the exhibition was not overwhelming, it traveled throughout the

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[31] Henry Russell Hitchcock and Philip Johnson, *The International Style* (originally published under the title: *The International Style: Architecture Since 1922*) (New York: W. W. Norton, 1995), 20.

[32] Mary Mix Foley, *The American House* (New York: Harper & Row, 1980), 241.

country and was outlined in an associated publication entitled, *The International Style*. The publication served to disseminate early ideas about the style, but also provided a lasting tribute. The moniker that they chose, "International Style," reflected the global distribution and perspective of its early practitioners—and perhaps due to aspirations held by Hitchcock and Johnson—for its future proliferation. The roots of the International Style can be traced to earlier movements occurring largely in Holland, France, and Germany, such as the Bauhaus, De Stijl, and the aesthetics of cubism and constructivism. Also influential was experimentation in reinforced concrete lead by Adolf Loos and Le Corbusier, as were the use of steel and glass and the standardization of building components pioneered by individuals such as Walter Gropius and Adolph Meyer.[33] As *The International Style* publication announced, "Today a single style has come into existence. The aesthetic conceptions on which its disciplines are based derive from the experimentation of the individualists. . . . This contemporary style, which exists throughout the world, is unified and inclusive, not fragmentary and contradictory like so much of the production of the first generation of modern architects."[34]

The book outlines the three principles of International Style, beginning with volume. The concept of volume relates to structure. In the past structural support was provided by the walls of a building. The International Style utilized the skeleton or framework of the building, usually constructed in metal or concrete, to provide support. These supports appear as a grid of vertical and horizontal members, exposing the true character of the construction. The beauty of this system was that it freed the structure of its load-bearing walls and thus allowed open interior floor plans and the realization of large sections of wall in glass. Sections of glass were countered by solid walls, generally covered in white stucco formed to provide a continuous overlay, becoming a hallmark of the style. According to Hitchcock and Johnson, "This concession to the principle of achieving a smooth continuous surface is an important instance of the exaggeration of the functionalist's anti-aesthetic claims."[35] Windows became the most visible character defining detail feature, punctuating the otherwise bare walls and defining a rhythm, which leads to the second principle, regularity.

Free of many of the interior walls that were necessary to the support of traditionally constructed buildings, International styled structures were not tied to the symmetry that had defined earlier buildings. On the contrary, if form was to follow function, maintaining symmetry would prove difficult. According to our authors, "The natural expression of the various functions grouped in one building is *not* symmetrical."[36] Thus, as they further noted, "technically the prime architectural problem of distribution is to adjust the irregular and unequal demands of function to regular construction and the use of standardized parts."[37] Moreover, symmetry was considered synonymous with monotony. Instead, buildings were to follow a certain regularity that would create aesthetic interest. Because rooms are generally broader than they are tall, a horizontal orientation became another character defining feature of the style. The horizontal nature of the structures was further emphasized by banding or broad expanses of windows and/or glass walls.

The third principle of the International Style is the avoidance of applied decoration. As an alternative, decoration was defined as all the "incidental features" of the design that provide interest.[38] The authors further argued against applied ornament by claiming that the quality of the execution of such details had declined significantly since the mid-eighteenth century. Perhaps this was true also because construction technology had evolved in a manner such that ornament had lost its functional quality and the aesthetic associated with its

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[33] Ibid., 241.
[34] Hitchcock and Johnson, *International Style,* 35.
[35] Ibid., 65.
[36] Ibid., 72.
[37] Ibid., 71.
[38] Ibid., 82.

production (as indicated by the term "applied decoration"). Instead the contrast needed to provide architectural interest was obtained through the use of varying materials presented in their natural form. White walls were thought to create a less striking contrast with the natural environment, while at the same time highlighting complimentary materials such as wood, metal, and glass. Traditional ornament was replaced by more subtle designs focused on window style and arrangement, and on horizontal axis. Window style included clean-cut, flush mounting and ribbon banding. A horizontal axis was further accentuated by utilizing a flat and/or parapet roofline. Porches and terraces that melded the interiors with the out-of-doors also helped the International Style building to blend with its environment.

Focusing on the nature of the building materials and stripping away the applied ornament lends an element of simplicity to the International Style that is in harmony with the precepts of traditional Japanese architecture. As noted Bauhaus-trained German architect Bruno Taut commented after a visit to Japan in 1933, "Japanese architecture has always been modern."[39] Indeed, the Japanese obsession with simplicity in the design of domestic architecture was first introduced in the fourteenth century by influential Zen Buddhist priests (known as the Muromachi and Momoyama periods). The movement "sought to eliminate the inessential and seek the beauty in unembellished humble things. It sought spaciousness in deliberately small spaces, and a feeling of eternity in fragile and temporary [wood] materials. A house's interior was not to be just protected from nature, but to be integrated with nature in harmony."[40] Removing unnecessary décor provided for a flexible use of space. Built-in cabinets provided storage and eliminated the need for freestanding furniture. Bedrolls could be brought out at night, allowing room for work and play during the day. Space was defined by the size of a standard tatami mat of 90 x 180 centimeters, which is considered adequate sleeping room for the average person. And in fact, every dimension of the Japanese house is relative to that of a *tatami* mat and thus based on the scale of the human body. Japanese traditionally favor wood as a building material, reflecting a deep-seated respect for nature. Thus, Japanese carpenters are noted for having perfected techniques for drawing out the intrinsic beauty of wood, often left in a rustic condition.[41] Integration with nature is facilitated through elements such as *shoji* screens and sliding doors "fusuma" that allow whole walls of the house to open onto it.

The Japanese Shoin style that developed during the Muromachi period (1336-1572) included distinct elements: a *tokonoma* or honored decorative alcove for hanging scrolls and other special objects; a *chigaidana*, staggered shelves located near the *tokonoma*; *chodaigamae* or decorative doors; a *tsuke shoin*, hanging shelf or built in desk; *shoji* screens; *tatami* mats; and *nakabashira* or interior supporting posts and *daikokubashira*, also referred to as *oyabashira*, a parent or mother post.[42] Other features appearing in Japanese houses are a *genkan* or entrance for welcoming guests that included a built-in cabinet for storing shoes; a *ji-bukuro* or low storage compartments appearing in the recesses between *tokonomas*; a *mizuya* or small kitchen with a cupboard and wash-up for tea utensils, and a *goemon-buro* or metal tubs heated from below by a wood stove. It was also during the Muromachi and Momoyama periods that the tea ceremony became more popular and that spaces within houses designed to facilitate such activities emerged. Tea rooms are entered through a *nijuri guchi* or a small doorway through which guests must enter on their hands and knees, thus requiring them to leave behind their (Samurai) swords and their egos in the pursuit of a pure and humble state of mind.[43]

Eventually the formal Shoin style gave way to a more relaxed Sukiya style, avoiding symmetry and repetition in favor of rustic simplicity. Along with it, the Sado or Chado "Way of Tea" sought to extend the "meditative

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[39] Geeta Nehta and Kimie Tada, *Japan Style* (North Clarendon, VT: Tuttle Publishing, 2005), 9.
[40] Ibid., 9.
[41] Ibid., 9.
[42] Ibid., 15.
[43] Ibid., 23-31.

simplicity" of the tea ceremony or *chanoyu* into every aspect of life to create harmony with nature and a retreat from the cares of the world.[44] These ideals strongly influenced arts and architecture in Japan. As one author describes it, "Contrary to Le Corbusier's adage of modern architecture, a traditional Japanese house is not simply a "machine to live in," but a home for the soul."[45] In fact, the traditional Japanese farmhouse or *minka* utilizes natural materials and building techniques that span hundreds of years.[46] *Minkas* are characterized by the use of a heavy wooden structural frame and thatched roof. Since their builders generally did not have access to the finest quality milled wood, *minkas* often incorporate large uncut or uneven timbers in their natural form, joined by mortise and tenon rather than metal fittings. The use of such materials and conditions helped to instill a reverence for joinery within the Japanese culture, as did their admiration for nature. Heavy thatched roofs were also an important part of Japanese aesthetic, and their deep overhangs provide protection from frequent rains and damp climate. Japanese roofs, now more likely tiled than thatched, generally do not include drains, using rain chains and gravel channels in the ground to carry run-off from the roof.

The relationship between the house and garden was also very important to the Sukiya style and thus great emphasis was placed on the landscape. Traditional Japanese house sites include a tea garden to mediate between the house and the outside world, separated by shoji screens. Shoji doors and windows are generally situated to take advantage of garden views or natural light. The garden plantings are intended to be a microcosm of nature, with thick moss carpets, larger evergreens, and low shrubs. Elements of the garden are accessed or joined by meandering paths or stepping stones referred to as a "rojo."

With the precepts of the International Style and elements of traditional Japanese architecture in mind, the influences that inspired the design and construction of the Nakashima complex speak directly to the Nakashima complex. Beginning with the Nakashima family house in 1946, followed by the Showroom in 1954, Conoid Studio in 1960, Arts Building in 1967 (and its associated Cloister in 1965), culminating with the jewel box Reception House in 1977, Nakashima combined these characteristic design elements. And in the case of the Conoid Studio in particular, Nakashima's designs also incorporated the innovative use of structural concrete. As with other proponents of the Modern Movement, Nakashima rejected the notion of style. According to Nakashima, "There is actually no 'modern' and no 'traditional,' but rather honesty and dishonesty of concept. When we speak of 'modern' it is again a style, and often as sentimental and 'traditional' as Cape Cod. Whatever styles and forms we have should evolve from the methods and materials used."[47]

George Nakashima and the American Craft Movement, 1945-1970

George Nakashima is recognized as one of America's preeminent furniture designer-craftsman, and a significant force within the American Craft movement of the mid-twentieth century. The post-war period from 1945 to 1969 is considered to be one of the seminal periods for woodworking in the United States, sometimes referred to as the "golden age," and Nakashima was one of its foremost contributors.[48] According the curator of American decorative arts at the Philadelphia Museum of Art, David Barquist,

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[44] Ibid., 20. As the authors relay, "In architecture chanoyu has generated a special style called the Sukiya style, known for its minimalism, simplicity, rusticity, understatement and restrained playfulness."

[45] Ibid., 18.

[46] The word *minka* originally meant a home of a common person who was not an aristocrat or a samurai; however, it is now primarily used to describe farmhouse with heavy wooden structure and thatched roofs. Nehta and Tada, 108.

[47] George Nakashima, "How We Treat Wood," *Journal of the American Institute of Architects* 18 (July 1952): 10.

[48] Glenn Adamson, "Gatherings: Creating the Studio Craft Movement," in Jean Falino, ed. *Crafting Modernism: Midcentury American Art and Design* (New York: Abrams in association with Museum of Arts and Design, 2012), 32.

> The postwar generation, seeking an alternative to the austerity of the Depression and war years, embraced wood as a more natural and traditional medium. A dazzling sequence of iconic landmarks in the history of American craft followed, beginning with Rude Osolnik's irregular wood turnings of about 1945 and George Nakashima's natural-edge slab-top coffee table of 1946, through the elegant lines of Sam Maloof's trademark rocking chair of 1963 and Wendell Castle's music stand of 1964. These craftsmen celebrated wood with a passion that became the identifying characteristic of makers of handmade furniture and turnings in the decades after the war." [49]

During the war and the Depression years that preceded it, both the demand for luxury and handmade goods and the supply of needed materials collapsed. The return to prosperity that followed the war brought both new possibilities *and* new building materials; developed for use during the war, materials such as plywood and plastics, and methods such as lamination and synthetic-bonding elements enabled the affordable mass production of furniture and other objects, quickly meeting rising demand for consumer goods.[50] Designers such as Charles and Ray Eames gained distinction with prefabricated designs now considered iconic. Many, however, saw the rise in mass production as a sign of a soulless society. As synthetic materials entered the home furnishings market during the 1950s and 1960s, Nakashima was among the few who continued to use traditional materials and production methods, and to reflect back to vernacular forms, albeit with a modern spin.[51] According to Glenn Adamson of the Victoria and Albert Museum in London, "Put simply, there was a sense of crisis about the future of the handmade." As with the previous Arts and Crafts period, craftsmen were determined to restore valued traditions. As Holly Hotchner, Director of the Museum of Arts and Design summed it up: "In the period immediately after World War II, the crafted object, and the process of making things by hand, became an invigorating counterbalance to wartime experiences and privations, the homogeneity of mass-production, and the creeping alienation of suburban and corporate life."[52]

Many of the craftsmen of the post-war period worked alone to create unique objects, and were motivated not by the promise of fame and fortune, but by their search for self expression within an increasingly alienating society. Nakashima referred to himself as a "woodworker" rather than a furniture designer or craftsman. This notion resonated with many others working in the field, most of whom were self-taught or minimally trained (although the GI Bill did provide training opportunities and colleges now created fine arts programs that offered such coursework).[53] Nakashima was among the exceptions, having been trained in architecture. The "woodworker" moniker reflected Nakashima's life-long commitment to the subjugation of the ego as a means to developing his creative force. Nakashima's exposure to eastern religion and Japanese craft traditions taught him not only the value of rejecting one's ego, but of seeking peace, beauty, and harmony through one's work. As Nakashima explains it, "The key to fine workmanship lies in the drive for perfection and the development of skills to achieve it. Perhaps as a backlash to industrialism and commercialism, a new concept seems to be taking hold."[54]

It was perhaps Nakashima's all-encompassing approach to his life and work that resonated with craftsman of the post-war era and that made him so revered. In an interview with *Life* magazine in 1970 he urged his fellow

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[49] David L. Barquist, "Druids and Dropouts: Working Wood, 1945-1969," in *Crafting Modernism*, 226-245.

[50] Tastemakers, Mary and Russel Wright's 1950 *Guide to Easier Living* (1950) emphasized the convenience and economy of mass-produced goods as the best solution to meeting the demands of modern life.

[51] Ostergard, 64-65.

[52] Holly Hotchner, "Foreword," in *Crafting Modernism*, 14.

[53] Barquist, "Druids and Dropouts," 227.

[54] George Nakashima, "The Soul of a Tree" in *The Craft Reader*, 224.

craftsmen to get away from the trappings of civilization and "enjoy the nature and the life of the spirit." According to Nakashima, "I think there are times when one should go underground when he can't stand what is going on in the outside world."[55] As with the Arts and Crafts movement, those working in the post-war era felt that industrialization needed to be counter-balanced with handicrafts and thus there was a growing discussion about the role of the craftsman in an era of mass production. According to Matilda McQuaid, Associate Curator of Architecture and Design at MoMA, "this intensity of mass production during the 1940s and the infusion of new materials created if not a backlash then a yeaning by both consumer and craftsman for natural materials and the irregularities of handcrafted objects during the postwar period."[56]

The furniture designs employed by George Nakashima reflect a variety of influences. Often defined as "organic naturalism," his timeless pieces really defy stylistic categorization. At the same time, some designs hark back to American classics such as the Windsor chair and the (also timeless) Shaker "plain style," both of which are known for their economy of design and the conspicuous use of elements such as tenons and dovetail joints.[57] Likewise, much of Nakashima's design work reflects the Arts and Crafts Movement ideal of combining beauty with functionality. Believing in the spiritual qualities of wood, Nakashima's signature features incorporated techniques intended to diminish human impact upon wood's natural beauty, by use of the "free-edge" and the butterfly inlay. The wood was cut along the grain to form large, monolithic slabs and elements generally viewed as imperfections such as knots and splits were celebrated. His signature butterfly joints were also often used to connect two mirrored segments of a tree to create large pieces such as dining tables. Nakashima believed that the beauty of the natural wood spoke for itself; his role was to utilize it in a way that highlighted that fact. As he explained it in an interview with *Life* magazine,

> The direction of cut, the thickness of cut, all these things are very important. The growth lines of winter, when a tree is growing slowly, give the grain its bands of darker, harder wood. The summer growth is wider, lighter, softer. And because of all the strange twists inside even trees that look very straight, all these differences became exaggerated and beautiful in the cutting. In root wood and crotch wood, those places where a tree changes direction, you find a different grain, a shimmering burl-like grain. But every board is unique and there are always surprises.[58]

Thus, Nakashima is typically known for using wood as close to its natural state as possible; retaining the free edge of the tree in order to capture its natural elements and configuration was a major component of that philosophy. According to Nakashima, cutting the wood " is like cutting a diamond."[59] This tendency is a reflection of Nakashima's Japanese heritage; as he explains, "To leave a piece of wood alone, simply for its own value, is rather Japanese. In Japan there is a reverence for wood and a gentleness toward nature that we don't have here in the west."[60]

At the same time Nakashima and others of the post-war era embraced Modern stylistic influences and ideas that were international in scope. Modernism originated in Europe through movements such as the Bauhaus and

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[55] "The Craftsman: Fulfilling our Need and Nostalgia for Wood," *Life* 68 (June 12, 1970): 78.
[56] "Matilda McQuaid, "George Nakashima and the Mass Production of Craftsmanship," in James A. Michener Art Museum, *George Nakashima and the Modernist Movement* (Doylestown, PA: James A. Michener Art Museum, 2001), 16.
[57] Steven Beyer, *George Nakashima and the Modernist Moment* (Doylestown, Pennsylvania: James A. Michener Art Museum, 2001), 12. Nakashima's designs for chairs in particular are reminiscent of traditional American designs such as the Windsor chair or chairs crafted by Shaker craftsmen.
[58] "The Craftsman: Fulfilling our Need and Nostalgia for Wood," 78.
[59] Ibid.
[60] Ibid.

many of its artisans and architects immigrated to America in the post-war period. Imported Danish modern, for example, became a touchstone of modern design by the 1950s.[61] As in the European Modernist tradition, Nakashima espoused a minimalist, utopian vision of design for the common man. As Ostergard characterizes it,

> Nakashima's work may owe a debt to both East and West, but in fact, his designs of the last half-century have been international in scope, timeless in quality. Balanced on the cusp of two cultures, the disparate methodologies of craftsmanship and mechanization, and the differing personal motivation of a lover of nature and a trained architect, Nakashima and his aesthetic have retained its vivid validity and consistency. Ultimately it has been the mixture of all these factors that has made his work unique, despite his professed lack of interest in individual statements.[62]

In his seminal work, *The Soul of a Tree* and in other venues Nakashima helped to outline a new paradigm for studio furniture design and production. In her essay for the James A. Michener Art Museum's publication *George Nakashima and the Modernist Moment,* McQuaid discusses three particularly significant events that helped define George Nakashima's role in the movement. The first was his participation in MoMA's path-breaking 1951exhibition *Design for Use, USA*, which traveled throughout the United States and in Europe. It was extremely influential in part because it was the first MoMA exhibition about American design that placed emphasis on those items "that were typically, even particularly, American."[63] The exhibition was also intended to deliver an important message about the designer-craftsman as both "an aid to manufacturing and a corrective to its dehumanizing effects, a message that drew equally from the legacies of the Bauhaus and the Arts and Crafts movement."[64] It was a message that Nakashima also espoused and for which he would continue to advocate. The exhibition included three of Nakashima's best known pieces: the "High Mira" three-legged stool, which was one of the earliest designs produced in his New Hope studio and was inspired by the classic American Windsor chair; and two of his pieces from his first major commission in 1941 for Andre Ligne, a walnut chair with cushions, and a walnut occasional chair with a grass seat. Nakashima's adherence to tradition and his independent studio production set him apart from many of his contemporaries who were also included in the exhibition yet designed for mass production.

Next, Nakashima was included in a landmark study undertaken by Walker Art Center in Minneapolis in cooperation other major museums, which in a similar mode to the MoMA exhibition, focused on how product design could be substantially improved by craftsman and industry working together. As both a proponent and successful model for the role of the craftsman in the world of industrial production, Nakashima was among the prominent American designers examined by the Committee on Design and Craftsmanship. The study culminated in a publication entitled *A study of Design and Craftsmanship in Today's Products*, and included an accompanying film and a conference. Among the objectives of the study was to discover "the ways in which individual designer-craftsman contribute to the production of well-done things by perpetuating the traditions of craftsmanship and by exploring new directions in form and technique."[65] Nakashima's work was used to illustrate ideas about the artist-craftsman as successful designer-producer. While dedicated to craftsmanship, Nakashima understood the role that mechanized processes could play in handcrafted work. He was very willing

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[61] Todd Merrill and Julie V. Lovine, *Modern Americana: Studio Furniture from High Craft to High Glam* (New York: Rizzoli, 2008), 19.
[62] Ostergard, *George Nakashima*, 86.
[63] McQuaid, "George Nakashima," 20.
[64] Glen Adamson, *The Craft* Reader (Oxford and New York: Berg Publishers, 2010), 36.
[65] Unpublished prospectus titled "Design and Craftsmanship," sponsored by the Committee on Design and Craftsmanship, 3-4, Museum of Modern Art Library, New York, NY, as cited in McQuaid, "George Nakashima," 22.

to utilize machine tools in his furniture production "as long as the intrinsic qualities of the material were not compromised by the lack of individual wood selection, hand detailing, sanding, and finishing."[66]

According to McQuaid, George Nakashima's impact was also recognized by his participation in an important and well attended conference held in New York in 1953 on the influence of design on better living. Nakashima gave an address, entitled "One Man's Answer," which was followed by a panel discussion about the roles of art and design. Along with Nakashima, the panel included preeminent industrial designer Henry Dreyfuss; president of Steuben Glass, Inc. Arthur Houghton, Jr., and California architect Paul Williams. In his address, Nakashima expressed the view that "American civilization was spiritually deprived and motivated primarily by its materialism" and made an appeal for "a more integrated approach, not only to design and the manufacturing process, but to life itself."[67] Nakashima advocated for a balance between art and design, culminating his talk with the following statement:

> We must adapt to our experiences and our technology. To accomplish this, as I see it, a whole new environment has to be created, an environment not based on the sentiments of the spinning wheel but also not based on sentiments and tyrannies of the production line. Rather an environment which provides a synthesis of what is good for us as human beings, who are in control of their environment, not victims of it.[68]

Numerous other important events helped to shape and define Nakashima's career as a national significant designer-craftsman. In 1946 Nakashima established a relationship with H.G. Knoll Associates, a furniture manufacturer in New York City. Knoll mass-produced some of Nakashima's designs, although custom production and sales of his furniture continued at the New Hope workshop. H.G. Knoll had a similar relationship with a number of highly regarded Modern furniture designers of the mid-twentieth century.[69] In addition to Nakashima, these included Isamu Noguchi, Eero Saarinen, Robert Venturi, and Ludwig Mies van der Rohe, to name a few of the best known. As Mira Nakashima informs us, "Shu [Florence] Knoll was the driving force behind the Knoll planning unit. She wanted serious quality in everything that the company made, and she recruited artists of the highest caliber to design for it, among them the architect Alvar Aalto, the sculptors Harry Bertoia and Isamu Noguchi, and my father."[70] Although Nakashima eventually decided to end his relationship with Knoll and return to independent work, it was an important experience; it both presented his work to a broad and discriminating audience and provided important lessons about furniture manufacturing and marketing. As Mira explains it, "Nakashima's collaboration with Knoll ended in 1954, but his association with Knoll was a fruitful one. It gave my father the opportunity to see how craftsmanship and industry could work together, and how a serious designer could produce pieces of genuine quality for the mass market."[71]

Perhaps a factor of the lessons learned during his venture with Knoll, it was also about this same time that Nakashima developed furniture catalogs. The first in 1945 was a small, six-fold blueprint design. In 1951 Nakashima issued a book-form catalog that featured ten new items, and the next catalog, issued in 1955,

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[66] McQuaid, "George Nakashima," 23.
[67] Ibid., 25.
[68] "Nakashima's Solution: His Own Woodworking," *New York Herald Tribune*, October 25, 1953, as cited in McQuaid, "George Nakashima," 24.
[69] The corporate headquarters for Knoll, located in East Greenville, Pennsylvania, was contacted in an attempt to retrieve sales and production data regarding the relative success of Nakashima's designs versus other designers at Knoll; however, this data was not available. Elizabeth Needle and Linda F. Kasper to David Kimmerly, electronic correspondence, 2008.
[70] Mira Nakashima, *Nature, Form & Spirit*, 76.
[71] Ibid., 77.

introduced twenty-one new designs. Interestingly, the delicate line drawings used in the 1955 catalog reflect the fact that the character of the final product was subject to the selection of the wood and the needs of the client rather than being rigidly fixed.[72] Also running counter to the "mass-production" of Nakashima pieces for Knoll was his development during this period of one of the most important designs of his career, the Slab Coffee Table. As Ostergard commented, "it was his expanded use of the free edge that revealed his most important artistic growth at this stage."[73] Likewise his use of the butterfly joint as both a functional and decorative element had become an integral component of his designs. According to Ostergard, "although Nakashima was not the first designer to employ it, he developed it more fully than anyone else."[74]

By the early 1950s, Nakashima had distinguished himself as one of the most important furniture designers in the country. This was accomplished through the high quality of his work and by the model that he provided as an individual dedicated to his craft—qualities that Nakashima would surely argue must go hand-in-hand. As McQuaid states, Nakashima became the silent voice of the artist-craftsman—frequently referred to as such in publications and often depicted as the artist in creative isolation who desired distance from activities that took him away from work and family."[75] While Nakashima's recognition by the public was not as great as designers such as the Eameses or Saarinen, considering that his pieces were individually crafted while their designs were mass-produced, his influence was remarkably far-reaching. More so then many of his contemporaries, Nakashima's "presence and his commitment to his ideals came to be regarded by many as a seminal influence on studio craft after the war."[76] Nakashima's acclaim can also be attributed to his involvement with Knoll, which constituted an endorsement of his work at the highest levels of Modern furniture design. Working with Knoll also provided Nakashima an opportunity to prove that industry and craft could be integrated in a manner that contributed to the quality of both. Another such opportunity was soon to present itself.

In 1957, George Nakashima was approached by Widdicomb-Mueller Company of Grand Rapids, Michigan and asked to design a line of furniture, also intended for mass production, similar to the arrangement he had previously negotiated with H.G. Knoll. As with that venture, Nakashima was able to test and to refine his own beliefs about craftsmanship and industry. Incorporated in 1873, the Widdicomb Furniture Company was located in what was historically the center for furniture manufacturing in the United States. By the late nineteenth century, it claimed to be the largest manufacturer of bedroom furniture in the world. Although the operation was largely mechanization by the early twentieth century, the decorating and finishing was still done by hand in order to create high-end pieces. In the 1920s they began producing some Modern designs and within a decade were producing them exclusively. The company contemplated using thirty-five different designers before selecting George Nakashima. The resulting *Origins* line, which included full suites of furniture, was introduced on June 12, 1958 at the Furniture Fair in Grand Rapids.[77] It was also featured on the cover of the October 1958 issue of *House Beautiful*. Although clearly modern, the *Origins* line, like all of Nakashima's work, was considered timeless; the company referred to it as "a new 'American look' that despite its traditional inspiration was 'a boldly modern approach'" to design. As with Knoll, the relationship with Widdicomb-Mueller was constructive for Nakashima "allowing him to broaden his base of support among consumers and

[72] Ostergard, *George Nakashima*, 69.
[73] Ibid., 63, 69.
[74] Ibid., 70. As Ostergard also points out, in the past the butterfly joint was used primarily as a remedial joint to repair a split piece of wood; rarely was it used as a primary joint in the construction of furniture.
[75] McQuaid, "George Nakashima," 25.
[76] Ostergard, *George Nakashima*, 58.
[77] There is little to no sales or production data available to verify the relative success of the line in the Widdicomb Furniture Company archives, which are located at the Grand Rapids Public Library in Michigan. Ruth Van Stee, Grand Rapids Public Library, to David Kimmerly, electronic correspondence, 2008.

critics" alike.[78] Moreover, as Matilda McQuaid described it, "his work for Widdicomb-Mueller seemed to go beyond just a financial benefit and became a test of his beliefs about the craftsman's maintaining control over the machine and ultimately assuming the responsibility for the final product. As McQuid concludes, "Ultimately, Nakashima always saw himself as a woodworker."[79] He soon returned to studio production and the *Origins* line was discontinued. As Ostergard points out, "Nakashima's dual role as designer and producer may have kept his operations vital. This may be why Nakashima also limited the scale of his operations. By so doing, he has been able to retain a strong degree of control over the output of his firm."[80]

Among the other significant indications of Nakashima's achievement in the field was his inclusion in an exhibition by the Renwick Gallery of the Smithsonian Institution in 1972 entitled *Woodenworks.* The Renwick Gallery is devoted to the study and presentation of American design and crafts and significantly *Woodenworks* was its inaugural exhibition. It featured the work of five preeminent craftsmen, all working in wood and all of whom were noted for combining modern forms with traditional materials and skills; they included: Wendell Castle, Arthur Espenet Carpenter, Wharton Esherick, Sam Maloof, and George Nakashima. According to the accompanying publication, the Renwick curators were responding to the "new awareness" about the role of the professional craftsman in society. They stated that "Today, when plastics so often take the place of wood and ape its appearance in commercially produced furniture, it seems fitting to take a fresh look at the familiar traditional material as handled by master craftsmen to recover some sense of that special quality generated from a mating of individual creativity with fine natural material." Also important indicators of Nakashima's acclaim were two exclusive exhibitions of his work, one just before and the other following his death in 1990. The first was New York's American Craft Museum's *Full Circle*, a fifty year retrospective (1989); and secondly, the James A. Michener Museum's *George Nakashima and the Modernist Moment* (2001). Nakashima was also included post-mortem in the Boston's Museum of Fine Arts *The Maker's Hand: American Studio Furniture, 1940-1990*, in 2003. *The Maker's Hand* exhibition also appeared in book form and has been called the most authoritative publication to date about the Studio Furniture movement. It states "To connoisseurs of modern furniture, names such as Wendell Castle, Wharton Esherick, Sam Maloof and George Nakashima are signposts to a revolution in the decorative arts that remains one of the most vital of our time."

In addition to exhibitions, George Nakashima has been the subject of numerous publications, and has in fact been featured in every noted publication on the craft movement and fine woodworking in America. Publications which featured George Nakashima as the sole subject include: Steven Beyer, *George Nakashima and the Modernist Moment;* Mira Nakashima, *Nature, Form & Spirit: The Life and Legacy of George Nakashima;* and Derek E. Ostergard, *George Nakashima: Full Circle*. As already mentioned, he was also involved in an influential study organized by the Committee on Design and Craftsmanship titled "A Study of Design and Craftsmanship in Today's Products" presented by the Walker Art Center in Minneapolis. Nakashima is also celebrated in numerous compendiums of the studio craft movement in addition to the ones mentioned above, including: *The Craft Reader*; *Crafting Modernism: Mid Century American Art and Design*; and *Modern Americana: Studio Furniture from High Craft to High Glam.* In addition, the George Nakashima House, as part of his craft legacy, has also been featured in: *Esherick, Maloof, Nakashima: Homes of the Master Wood Artisans* (2009); *Handcrafted Modern: At Home with Mid-Century Designers (2010); and Artists' Handmade Houses* (2011).

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78 Ostergard, *George Nakashima*, 72.
79 McQuaid, "George Nakashima," 29.
80 Ostergard, *George Nakashima*, 64.

Finally, among the most significant recognitions that George Nakashima has received for his work as a master American craftsman is the American Institute of Architect's Craftsmanship Medal, which he received in 1952. As stated in the citation: "You have perpetuated in your work in the design and making of furniture the high standards of past ages of handcrafts, and that respect for good materials and honest labor . . . that will in any age distinguish great craftsmanship."[81] George Nakashima won many other awards for both his furniture design and for his architecture. Among these are the Silver Medal of Honor in Design and Craftsmanship given by the Architectural League of New York, 1960; Catholic Art Association Medal, 1969; listing in *Who's Who in America*, 1975; Gold Medal and title of Japanese American of the Biennium in the Field of Arts, San Francisco, 1980; Honor Award for Inspired Creativity Outstanding Sensitivity in Design, The Pennsylvania Society of Architects of the American Institute of Architects, 1981; Bucks County Distinguished Service Award, 1985; and the University of Washington Alumnus Summa Laude Dignatus, 1990.

As a collectible item, Nakashima's work is highly prized and valued today, despite his insistence that his furniture first be useful. As Mira Nakashima explains, "My father said that his furniture should not be considered overly precious and that it was meant to be lived with. . . . Ironically, some of Nakashima pieces today are now considered works of art, at least for insurance purposes. . . . There are many stories of how this piece or that piece created a peaceful atmosphere in a client's home or office (except when squabbles later arose over who would inherit it)."[82] A check of David Rago's auction house web site located in nearby Lambertville, New Jersey, which handles Arts and Crafts and Modern furniture, reveals just how valuable Nakashima furniture is in today's collectible market: walnut floor lamp with white paper, $25,000; set of four high Mira walnut chairs, $17,000; walnut double chest of drawers, $14,000; and English walnut side table with free edge, $14,000. Furniture made by Nakashima became popular among the progressive upper and middle class, including doctors and lawyers, as well as other artists. For example, in the estate of Andy Warhol there was a Nakashima coffee table, and artist Ben Shahn owned several Nakashima pieces. One of George Nakashima's more notable commissions was for Nelson Rockefeller who hired him in 1974 to design furniture for the New York governor's Japanese style house in Pocantico Hills, New York.

Due to George Nakashima's spiritual and religious nature he designed altar rails, benches, pews and tabernacles for several churches in Bucks County. In the mid 1980s he embarked on a mission to make six altars of peace, one for each of the world's continents. The first of these altars was crafted in 1986. It measured slightly over 10' x 10' and was made of two matching sections of a walnut tree that were connected by butterfly joints. The altar was installed in the Cathedral of St. John the Divine in New York City. The mission of constructing the altars has continued through the efforts of his children Mira and Kevin Nakashima. Mira, an architect and designer, also has continued to produce George Nakashima's furniture at the New Hope studio as well as executing and selling some new designs based on her father's philosophies.

Comparisons with Other Designer Craftsman

According to Ostergard, writing in *George Nakashima; Full Circle*, "While there were aesthetic corollaries between Nakashima's work and that of his contemporaries who evolved as designers, only a few noted craftsman produced work on the same individual, handcrafted basis during this period."[83] As already discussed, many of the furniture designers of Nakashima's era used the new materials that became available during the mid-20th century. Charles Eames, for example, used plastic and stainless steel, and designed furniture with simple shapes such as squares and rectangles. Eero Saarinen also used plastic but favored space-age lines such

[81] "The Craftsmanship Medal for 1952 to George Nakashima," *Journal of the American Institute of Architects* 18 (July 1952): 4.
[82] Mira Nakashima, *Nature, Form & Spirit*, 116.
[83] Ostergard, *George Nakashima*, 53.

as curves and circles; his tulip chair, which he designed for the H.G. Knoll Company, is an example. Jere Osgood, who, like Nakashima trained in architecture, attained recognition using lamination to create curvilinear forms. Ostergard rightly identifies Wharton Esherick as the closest comparison to Nakashima as a designer craftsman. And another designer-craftsman with whom Nakashima has been compared is Sam Maloof. In fact, Tina Skinner aligns the three in her publication *Esherick, Maloof, Nakashima: Homes of the Master Wood Artisans*, recognizing that the influential trio turned to traditional craft and woodworking at the same time that the United States was deeply embracing mass consumerism.[84] The three were likewise featured in *Woodenworks*, the Renwick Gallery's debut exhibition (and in various publications and compendiums of the craft), along with Wendell Castle and Arthur Espenet Carpenter.[85] George Nakashima, however, distinguished himself from even these designers by executing designs that are clearly modern with very simple streamlined shapes or a natural free edge wood shape, reflected in his unique experiences and worldview.[86] In addition, Esherick, Maloof, Carperter, and Castle are generally categorized as "studio artisans" while Nakashima is considered a "designer craftsman" due to foray into contract production and the size of his operation.[87] For the purposes of this nomination, moreover, there are limited numbers of craftsmen that also designed and built their own home and studio complexes. The most notable example, which has already been designated a NHL, is the Wharton Esherick Home and Studio (although the Eames House is also a NHL).

Wharton Esherick was an artist, furniture maker, and interior designer, and as the elder among this group, is said to have "pioneered the archetype of the self-taught woodworker."[88] Ostergard identifies numerous differences between Esherick and Nakashima, one of the most important perhaps being that Esherick had a "distinctly personal element to design" whereas Nakashima was more interested in anonymity (initially refusing to even sign his pieces). Esherick created one-of-a-kind pieces; while Nakashima worked from set prototypes, his pieces were made distinctive by the idiosyncrasies of wood with which he worked. In addition, Ostergard claims that Nakashima's work was "often veiled by vernacular or natural forms and the use of fundamental materials."[89] Esherick attended the Pennsylvania Academy of Fine arts and began his career as a graphic artist and painter. He first used carving tools to craft frames that would compliment his artwork, turning then to woodcuts and eventually to furniture design. While sharing Nakashima's respect for wood, Esherick's pieces

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[84] See: Tina Skinner, *Esherick, Maloof, Nakashima: Homes of the Master Wood Artisans* (Atglen, PA: Schiffer Publishing, 2009).

[85] Wendell Castle, like other craftsman who came of age in the 1960s, did not share the earlier generations reverence for wood. As he once stated, "It is important not to be subservient to a material. The significant thing about my work is not what it is made of but what it is." Lee Nordness, *Objects: USA—Works by Artist-Craftsmen in Ceramic, Enamel, Glass, Metal, Plastic, Wood and Fiber* (1970), 265, as cited in Barquist, "Druids and Dropouts," 231. Castle's work was regarded more for its artistic or sculptural qualities then for its functionality, as with Nakashima's furniture designs. As a result, Castle's pieces appealed to a smaller, more elite audience, designing what has been called "art furniture." Arthur Espenet Carpenter was a self-taught furniture maker who began his woodworking career turning wood bowls with a lathe in the San Francisco area. His signature style, known as the "California Roundover" incorporated curved lines and rounded edges. After about a decade of maintaining a successful business, in 1957 he bought a farm in Bolinas and began making furniture full-time. Claiming inspiration from Esherick and Maloof, Carpenter's designs were consider spare and practical, yet at the same time sleek and often artistic in nature. He too crafted his own home and workshop. The latter is a circular edifice with the kitchen at its core, encircled by contemporary, open-space rooms.

[86] Rude Osolnik is also recognized as a "pioneer in retaining feature of individual pieces of wood," but he was a wood turner and not a furniture maker. Barquist, "Druids and Dropouts," 227.

[87] Merrill and Lovine, 20. Other "designer-craftsman" discussed in this publication along with Nakashima include: Vladimir Kagan, Silas Seandel Paul Evans, and Phillip Lloyd Powell (the latter two worked together), although the authors comment that Nakashima was the most recognized among them. Also working in the New Hope area were Evans and Powell— the former was a metal sculptor and the latter a woodworker who combined their talents. Silas Seandel was also primarily a metal sculptor. Valdimir Kagan's style was sleek, organic and very modern, with an affinity toward the Danish modern designs then very much in vogue.

[88] Barquist, "Druids and Dropouts," 228.

[89] Ostergard, *George Nakashima*, 55.

often included ornamental carving in the Art Nouveau, Art Deco, and Cubist idioms, revealing a sculptor's sensitivity to form. In fact, Esherick considered himself foremost a sculptor.[90] Esherick's home, like his furniture, is almost sculptural and each component is handcrafted. Organic in form, it evolved slowly over a forty-five year time span. Esherick's home shares a fairly diminutive scale and simplicity with Nakashima's, but little else beyond the use of indigenous materials such as native stone. The adjoining Esherick workshop is, however, more aligned with the Modernist movement than the rest of the structure, having been designed with the help of Louis Kahn, albeit modeled after a stone barn. The Esherick complex is also far less extensive than Nakashima's; Esherick combined his residence and studio/gallery in one structure (also on site is a wood shed, out house, and log garage, now a visitor's center).

Sam Maloof worked during the same time period as Nakashima, beginning in 1945 until his death in 2009, and was also largely self-taught. Both received extensive press coverage, beginning in the late 1940s, in magazines such as *House Beautiful*, *Life*, *Look*, and *Newsweek*, as well as in art and architecture periodicals such as *Craft Horizons* and *Fine Woodworking*.[91] Likewise, both took advantage of machine tools and employed assistants in their workshops, created prototypical designs that have endured over time. Maloof too worked in his own home-based studio to create handcrafted designs in the modernist idiom, and was known for his innovative joinery. Unlike Nakashima who worked more in isolation, Maloof was part of a very active academic and artisan community that grew up around Claremont (California), encompassing Claremont and Scripps colleges, where many local artists taught and/or studied. Maloof entertained and had access to a broad range of artists, architects and designers. Maloof's home and studio is very different from Nakashima's; it is a sprawling California style contemporary that grew from a bungalow to a twenty-six-room timber frame house. Maloof added each room as he could afford it, now totaling 7,000 square feet, to house his extensive art collections as well as examples of his own furniture. In this regard, the Maloof House is very different for the sparse house that George Nakashima built for himself and his family. While Nakashima welcomed other artisans to his property, his compound includes numerous discrete buildings for family, guests, furniture display, and furniture manufacture.

Two other NHL sites are connected with modern designers: the (Charles and Ray) Eames House; and Manitoga, the Russel Wright Home & Studio. At the Eames House, located in the Pacific Palisades of Los Angeles, California, the "living component" or residence and the "working component" or studio are joined by an open court, unlike the complex of structures erected by George Nakashima that separates family, workshop, and studio space. The Eames House is significant architecturally as the most intact of the famed Case Study houses; the Case Study program was part of an effort undertaken by a number of noted architecture and design professions to promote modern architecture in the post war era by basically designing and building model homes. It is considered one of the most significant attempts to create experimental or demonstration homes in our nation's history.[92] The house, built in 1949, consists of a modular design with an exposed steel frame painted black with colorful infill in one of several materials; include plaster, plywood, asbestos, glass, and Pylon (translucent laminate similar to fiberglass). The interior has an open plan with living spaces on the first floor and bedrooms on the second. Comparisons between the Eames and Nakashima as furniture designers have already been discussed. Wright's Manitoga is also intended as an experimental house to demonstrate how American families could live better by utilizing basic principles of domestic economy and modern design. Wright was a highly influential mid-twentieth century industrial and interior designer best known for his

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[90] Carolyn Pitts, National Historic Landmark nomination for the "Wharton Esherick Studio," National Park Service, U.S. Department of the Interior, 1992, 13.

[91] Barquist, "Druids and Dropouts," 230.

[92] Elaine Jackson-Retondo, National Historic Landmark nomination for the "Eames House," National Park Service, U.S. Department of the Interior, 2006.

inexpensive, mass-produced household items and furnishings, and for his conviction that "good design is for everyone."[93] In that regard, Wright was more aligned with the Eames's approach to production than that of George Nakashima. With regard to the structure, a main block is connected by a wood pergola to a wing that serves as both master bedroom and workroom. Completed in 1960, the house is built into an abandoned quarry and has been described as "part cave, part forest pavilion, [a] rough hewn house that hugs the brow of a cliff over a secluded quarry pool [sheltering] nobly dramatic spaces which join the panorama of nature, change with the seasons."[94]

Working as solitary craftsmen in an isolated environment of their own making appears to have been a part of the persona of the designer-craftsmen of the post-war era, as indicated by the home and studio complexes of Wharton Esherick, Sam Maloof, and George Nakashima. The Eames and Wright houses, while personal residences, were intended to also serve as models for modern design and living. The Nakashima complex is unique in its International and Japanese influenced styling and its use of experimental concrete, but also by the fact that it includes numerous individual structures for living, working, studying, wood storage, and furniture display. The Nakashima site is also distinguished by the fact that it is not a museum—as are all of the other sites discussed—but a working operation. Mira Nakashima, a talented designer-craftsperson in her own right, has worked tirelessly to continue her father's unique legacy and to maintain the spirit with which Nakashima Woodworker was established. Moreover, all of these sites reflect the design philosophy and aesthetic of its maker and thus each is a fiercely individualistic, even idiosyncratic, set of structures that are one-of-a-kind and beyond comparison.

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[93] Kathleen LaFrank, National Historic Landmark nomination for "Manitoga (Russel Wright Home)," National Park Service, U.S. Department of the Interior, 2005, 12.

[94] Ibid., 4.

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Previous documentation on file (NPS):

__ Preliminary Determination of Individual Listing (36 CFR 67) has been requested.
_X_ Previously Listed in the National Register.
__ Previously Determined Eligible by the National Register.
__ Designated a National Historic Landmark.
_X_ Recorded by Historic American Buildings Survey: HABS No. PA-6783
__ Recorded by Historic American Engineering Record: #

Primary Location of Additional Data:

_X_ State Historic Preservation Office
__ Other State Agency
__ Federal Agency
_X_ Local Government
__ University
__ Other (Specify Repository):

10. GEOGRAPHICAL DATA

Acreage of Property: 12.2 acres

UTM References: Lambertville (NJ, PA) Quadrangle

Zone	Easting	Northing
1. 18	503541	4465576
2. 18	503885	4465781
3. 18	504056	4465459
4. 18	503707	4465269

Verbal Boundary Description:

The boundary for the proposed property includes all of Bucks County Tax Map Parcel numbers (TMP#) 41-36-77 and 41-36-87-13. Bucks County Tax Maps are available at Bucks County Courthouse, Board of Assessment, 3rd floor, 55 E. Court Street, Doylestown, PA 18901.

Boundary Justification:

The proposed boundary contains all of the resources historically associated with George Nakashima. Both tax parcels contain buildings designed by or associated with Nakashima and his family. No buildings with association to Nakashima were excluded. The boundary also includes natural and cultural landscape features that are integral parts of the setting which are part of the properties overall historic integrity.

11. FORM PREPARED BY

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Date: November 2007 (NR documentation); October 2012

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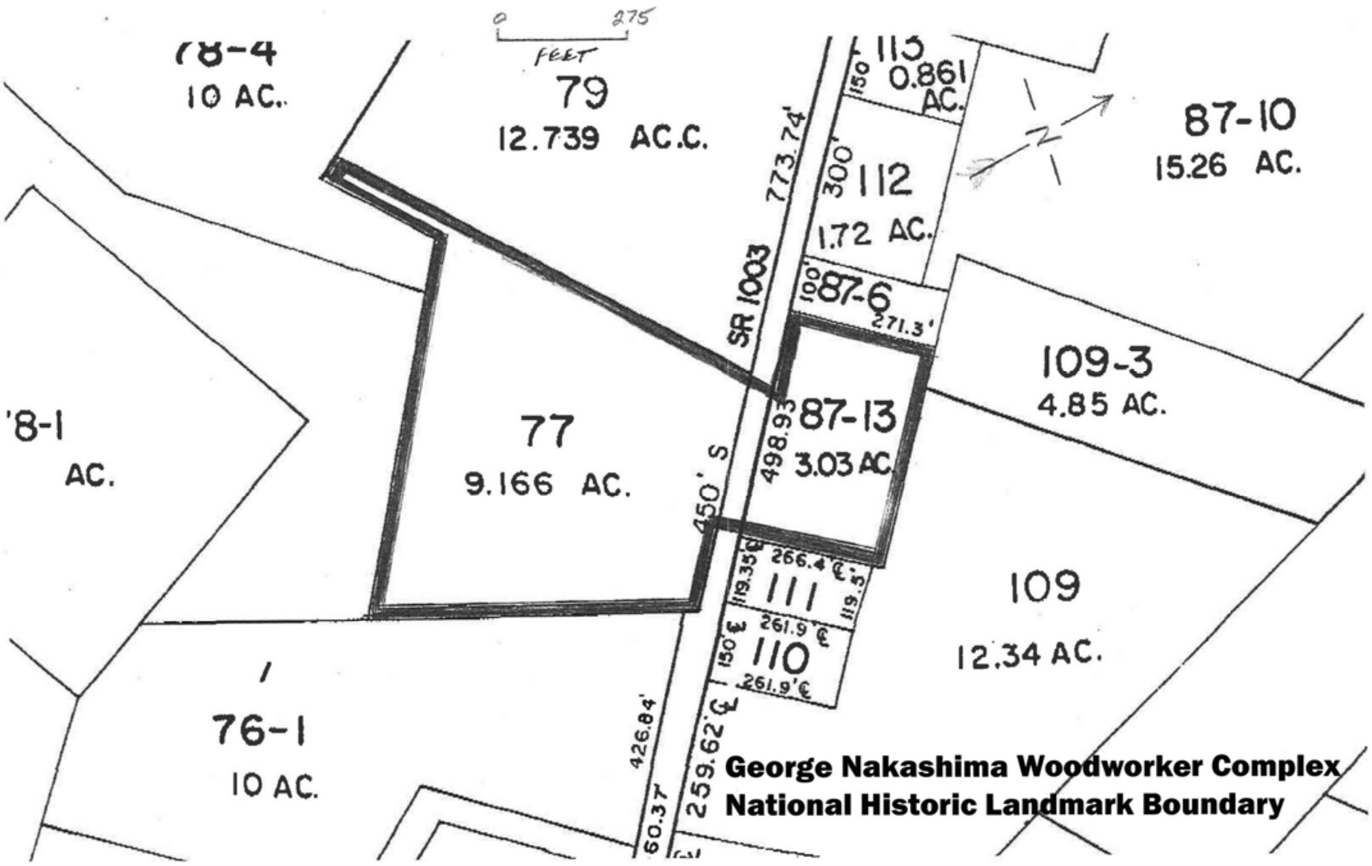
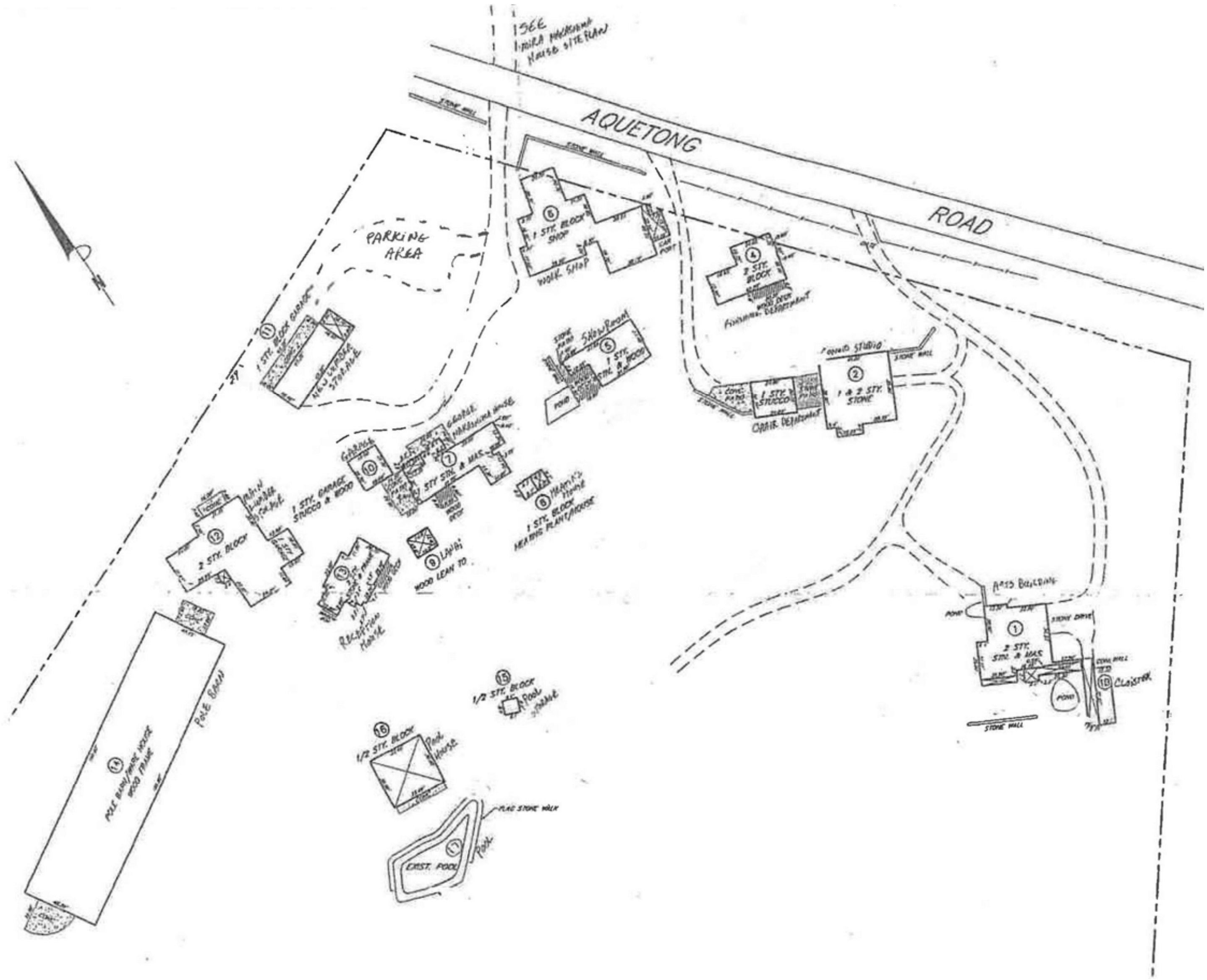
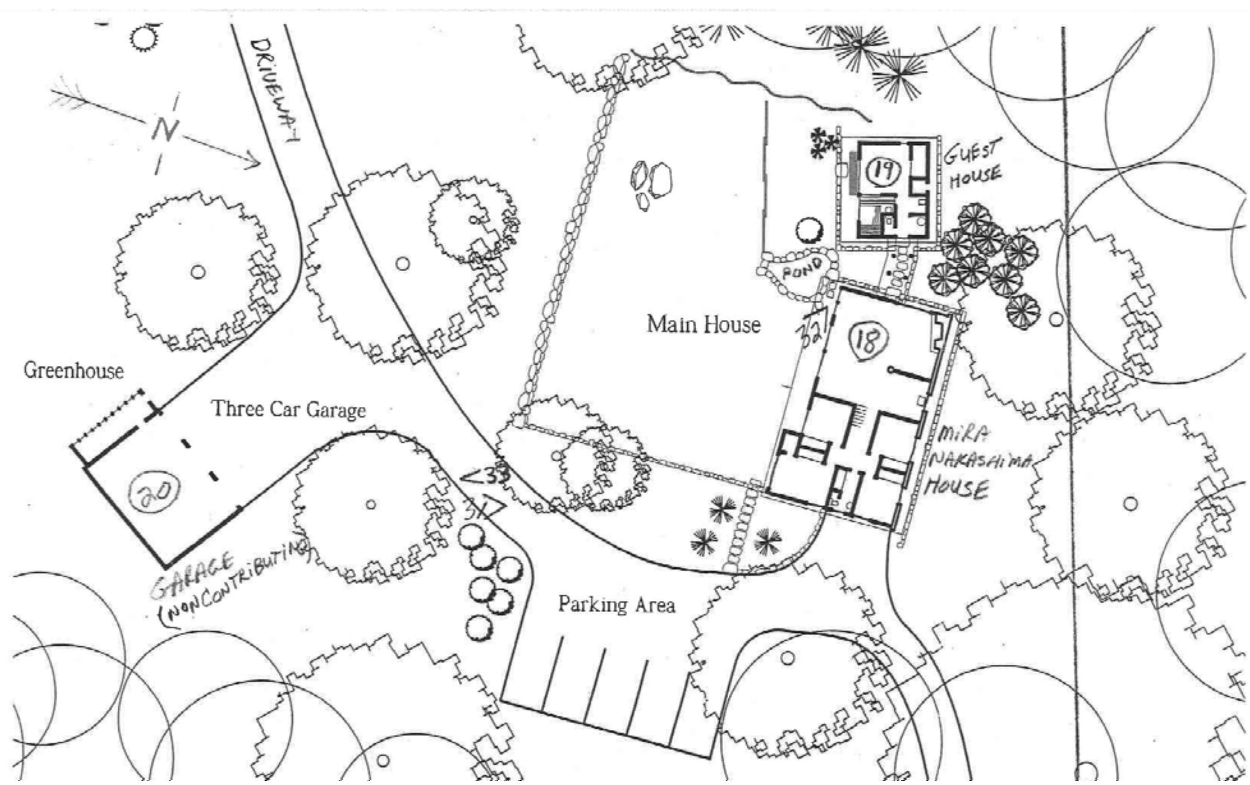
NATIONAL HISTORIC LANDMARKS PROGRAM
February 7, 2013



George Nakashima Woodworker Complex, Proposed NHL boundary, 2007, 2013



George Nakashima house and studio buildings, site plan, 2007

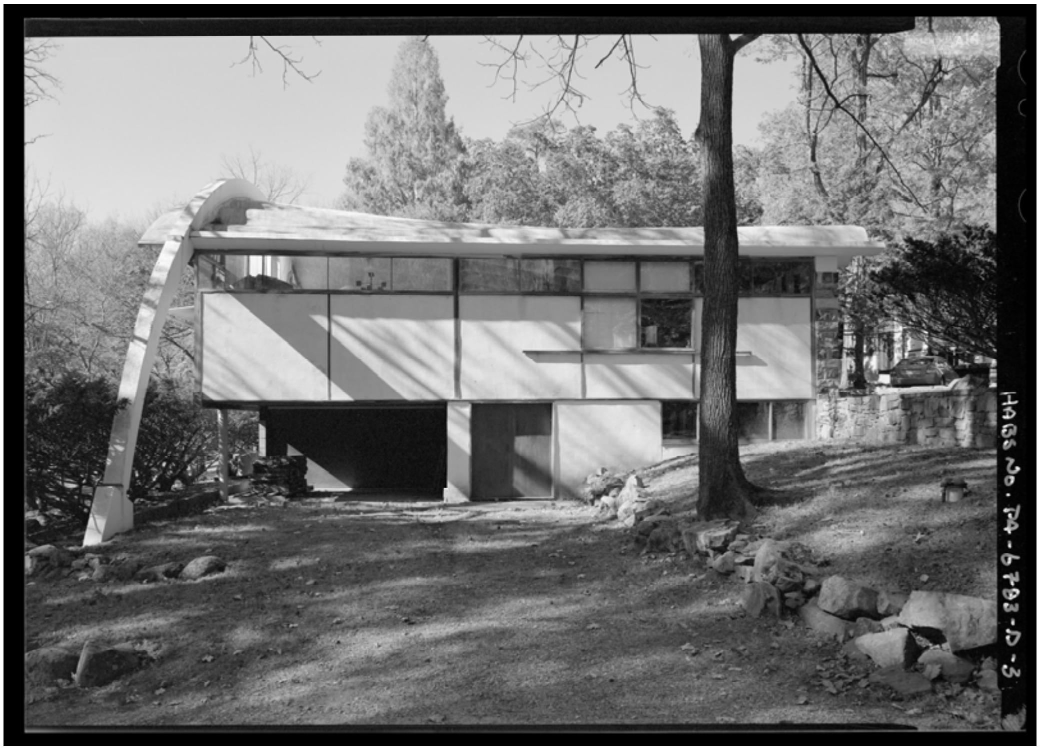


Mira Nakashima house, site plan, 2007

George Nakashima House, looking southeast
James Rosenthal, HABS, photographer, 2012

Workshop, looking north-northeast (above)
Detail view, Workshop interior, craftsman inserting butterfly joint (below)
James Rosenthal, HABS, photographer, 2012

Interior view, Showroom, looking west
James Rosenthal, HABS, photographer, 2012



Conoid Studio, side elevation looking west-northwest (above)
Interior view, Conoid Studio, looking southeast (below)
James Rosenthal, HABS, photographer, 2012

Arts Building viewed from the Cloister, looking north (above)
Interior view, Arts Building, looking west (below)
James Rosenthal, HABS, photographer, 2012

Reception House, looking west (above)
Interior view, Reception House, looking northwest (below)
James Rosenthal, HABS, photographer, 2012

A Scottish Wych Elm Burl Conoid Bench with back (above)
The first Peace Altar in the Arts Building before shipment to the Cathedral of St. John the Divine in New York City, 1986 (below)
Courtesy of Mira Nakashima, George Nakashima Woodworker, S.A.

The iconic Conoid chair first designed ca. 1960.
Courtesy of Mira Nakashima, George Nakashima Woodworker, S.A.

GEORGE NAKASHIMA
HOUSE, STUDIO
+ WORKSHOP
BUCKS COUNTY, PA

	Z	E	N
1.	18	503541	4465576
2.	18	503885	4465781
3.	18	504056	4465459
4.	18	503707	4465269