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Performance of Injection Adhesives for the Great Hall Ceiling at Drayton Hall, Charleston

JOHN HINCHMAN, FRANK G. MATERO, and ALEXANDER RADIN

For more than 25 years conservators have been using acrylic injection adhesives for plaster-ceiling reattachment with a limited understanding of the physical properties of these formulations.

Introduction

Since 1991 technical studies have been conducted at Drayton Hall, which was constructed between 1738 and 1742 and is located outside Charleston, South Carolina (Fig. 1). The goal has been to develop sensitive solutions for preserving the interior fabric of the house.[1] As part of this effort, the Architectural Conservation Laboratory of the University of Pennsylvania, which had documented and recorded the condition of the Great Hall's plaster ceiling in 1991, returned to the site in 2001 at the invitation of the National Trust for Historic Preservation to implement conservation treatments to the ceiling (Fig. 2). The 2001 project addressed both condition reassessment and treatment, and it included four principal tasks:

- Temporary stabilization to protect and support fragile areas of the ceiling during the installation of the structural retrofit and reinstallation of the wooden floor above. Supportive cushioned platforms were installed from below in the areas that had been identified as the most fragile to ensure that any vibration occurring during the reinstallation of the floor boards above would not result in greater damage to the ceiling.
- Condition reassessment to resurvey the ceiling conditions using the data from 1991 and identify any changes since the earlier survey. Additionally, all data, including the 1991 survey, was incorporated into digital drawings using Autodesk's AutoCAD and Raster Design. An experimental analysis utilizing GIS was also developed to verify the observations and assumptions about the ceiling conditions, causes of failure, and possible intervention strategies.[2]
- Treatment design and assessment to develop a program for evaluating and selecting an injection-grout formulation for reattaching loose sections of the ceiling. Using ASTM standards, mechanical tests were conducted to provide performance data on the treatments under consideration.
- Priority treatment implementation to address areas where failure was existing or imminent. These determinations were greatly influenced by the GIS analysis, which afforded highly predictive modeling of the collective conditions posing real and potential threats to the ceiling's stability. As a result of this analysis, the location of the structural retrofit and visitor access on the floor above was modified.

Fig. 1. Drayton Hall, Charleston, South Carolina, 2002. All images by the University of Pennsylvania Architectural Conservation Laboratory.

Summary Observations

Based on the 2001 survey, the following observations can be made regarding the existing conditions of the Great Hall ceiling.

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Fig. 2. Injection grouting of the Great Hall ceiling was carried out from below. Over 1,000 holes were drilled along existing cracks to create injection ports through which a canula was inserted to deliver the selected adhesive.

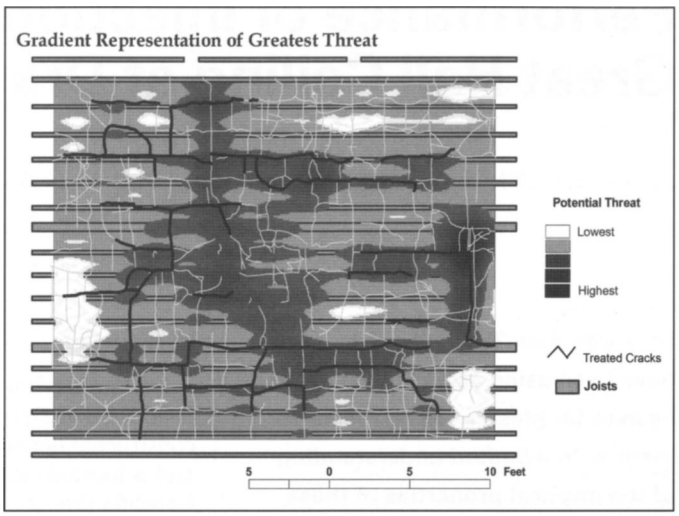

Fig. 3. Gradient representation of threat as determined by a GIS analysis. Note the high correlation between large cracks and detachment, which identifies two major areas of plaster failure and potential future damage across the center of the ceiling and under the fireplace hearth. Failure in these areas can be attributed to maximum joist bending (across the middle) and insufficient original keying (under the hearth).

A network of roughly orthogonal cracking appears across the entire ceiling (Fig. 3). Most of the large-width cracks run parallel to the long axis of the room and are closely associated with the joists located above them. Their slightly meandering quality suggests that they not only are below the centers of the joists but also occur to either side of a joist. This pattern can be explained by the differential movement from bending and shear cracking between undersized joists, as well as by tensile cracking across joists.

The condition of plaster detachment as determined by percussion is invariably associated with cracking, with a greater correlation between detachment and large cracks than any other crack type.

These overall conditions predate the opening of the house to the public in 1978, as evidenced in a 1938 Frances Benjamin Johnston photograph of the Great Hall. However, increased cracking and detachment could have occurred as a result of increased live load from visitors.

No quantifiable measurement of condition changes can be made between the 1978 stabilization and 1991, when a temporary bridge was installed to remove the live load from the second-story floor and the Great Hall ceiling below.

Analysis of the brown coat of plaster reveals a high clay-to-lime ratio that probably accounts for its high friability, very low tensile strength, and poor bond strength with the thin gypsum finish coat.

The stabilization treatments of 1978 reattached those areas with broken and removed keys (Fig. 4a) and areas where plaster detachment and voids were sufficient for the gypsum pour to flow between the underside of the lath and the brown coat (Fig. 4b). Any detachment of the ceiling caused by the release of the lath from the undersides of the joists would have been corrected by the continuous contact of the gypsum-mesh application to the top of the lath. The treatment did not reattach areas inaccessible to the pour or areas of keys with hairline cracks, scratch-coat separation, and narrow gaps. Moreover, hard-to-detect treatment failures, such as blind detachment, could have occurred between 1978 and 1991, before the temporary bridge was installed (Fig. 4c).

Research Design

In June 2002, after extensive structural analysis and design and installation of a thin plate system to stiffen the second-story floor and reduce vibration, remedial treatment to the detached areas of the ceiling was begun.[3] The first phase of intervention involved identifying locations in the ceiling where treatments would be necessary.[4] While initial treatment areas and methods had been specified following visual analysis and limited structural analysis, a final determination was made only after a comprehensive interpretation of the ceiling's condition, which used the results of the 1991 survey, the 2001 GIS analysis, an assessment of the 1978 treatment, and mechanical testing of the preferred adhesive formulations.

The GIS analysis provided an immediate, nondestructive method to identify areas of current and possible failure, as well as potential areas for reattachment based on observed correlations among cracks, detachment, and framing. This data allowed for greater selectivity in stabilization treatments. Understanding the existing conditions and creating treatment criteria to guide intervention played a major part of developing a comprehensive conservation plan. All components of the ceiling system were considered, including joists, lath, and plaster. While all of the recent conservation work, including the structural retrofit, would help to extend the life of the ceiling, it did not address the inherent material and construction problems. The original undersized joisting would

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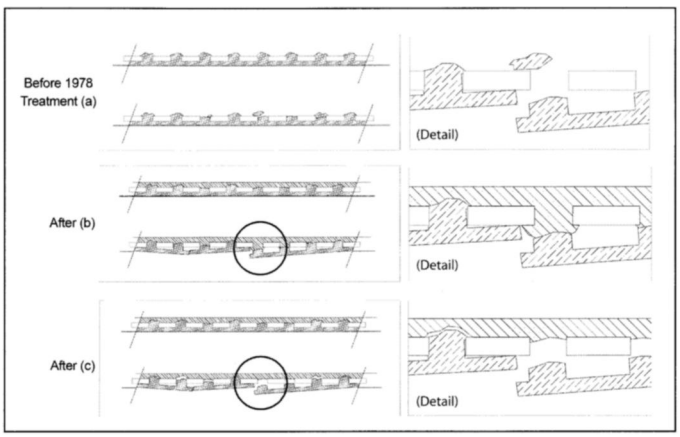

Fig. 4. Schematic sectional view of ceiling damage (a) before 1978 treatment, (b) repair after treatment, and (c) new damage after treatment.

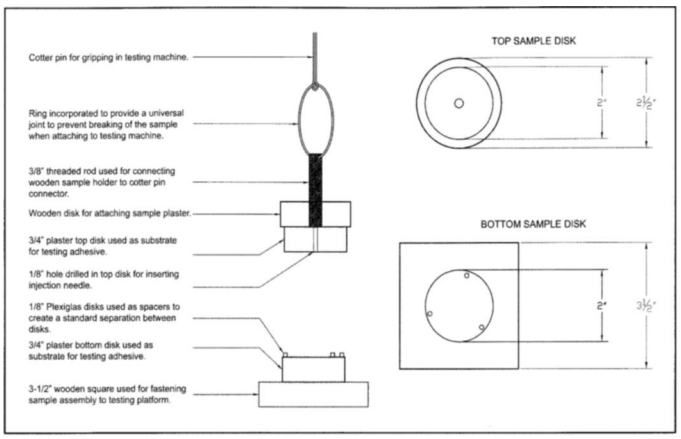

Fig. 5. Schematic of test specimen with assembly for testing tensile strength, per ASTM D2095-96.

still be undersized; the lathing would still be too close together; the brown coat would still be too lean a mix; and cracking could still occur in response to structural and thermal movement. Consequently, the best approach would be a conservative one that would address the ceiling's localized conditions and allow for additional treatment in the future should conditions change. The intervention carried out in 1978 treated the entire ceiling as a single entity. The current approach acknowledges that not all areas require equal intervention. In this way a more selective, minimal, and customized intervention could be achieved.

One limitation to the proposed work was that no treatment could be easily carried out from above. Although the second-story floorboards had been removed, the 1978 treatment, which involved pouring plaster of paris over wire mesh into the pockets between the joists, eliminated any future possibility of viewing or treating the ceiling from the second floor. Therefore, all new treatments needed to be conducted from the first floor. In order to reduce visual impact to the ceiling's surface, penetration of the plaster was to be limited to the damaged areas and the open cracking.

Research into past and current conservation methods for the stabilization of plaster walls and ceilings revealed a dearth of technical information, with little performance evaluation in the laboratory or field. Where discussed, plaster-reattachment materials and techniques were focused on masonry supports for mural paintings rather than on wood-lath systems.[5] One of the earliest and most frequently recommended methods for lath-plaster ceiling reattachment, a version of which was used to stabilize the Great Hall ceiling at Drayton Hall in 1978, was first described by William Millar in his classic text on plastering.[6] This method basically involves the application of plaster of paris with wire-mesh or burlap reinforcement to the back of the ceiling lath.

At approximately the same time as the 1978 Great Hall ceiling project, a new method of plaster stabilization based on the use of acrylic-dispersion injection adhesives was being developed by Morgan Phillips and was described in two seminal articles in the 1980s.[7] Over the past 25 years Phillips's technique has found widespread application in many important buildings in the United States (Appendix A). Yet despite its popularity among conservators, architects, and craftworkers, limited information exists on the mechanical properties of the formulations and their compatibility with various plaster-substrate systems. Moreover, little, if any, reevaluation of these treatments has occurred. Phillips himself recommended additional testing of his formulations to establish more defined parameters for future treatment selection and monitoring. This research is a step in that direction.

For the 2001 program at Drayton Hall, Phillips's methods and formulations were considered. The mixes use the same four basic ingredients, including two acrylic dispersions. Phillips's original formula contained Rhoplex MC-76 and Rhoplex LC-67 as the primary binders. Due to the discontinuation of LC-67, Rhoplex 1950 was substituted on the recommendation of the manufacturer. Rhoplex MC-76, originally designed as a masonry-bonding agent, imparts strength, while Rhoplex LC-67 and 1950, developed as binders for elastomeric sealants, add flexibility. Water and a thickener (Acrysol ASE-60) are added to control viscosity and flow. By varying the quantities of the two acrylic dispersions, Phillips attempted to develop two different formulations to address the varying degree of "flexibility," or, more correctly, elasticity, required to compensate for movement in the ceiling. Unfilled and filled formulations with various inert and reactive bulking agents were also designed to accommodate various detachments: small gaps where the existing distance between the plaster and substrate was less than 1/16 inch, as well as large gaps where the distance was much greater.

In the case of the flexible formulas, the mixtures were based on three parts Rhoplex MC-76 to one part Rhoplex 1950, while the "rigid" (Phillips's term) or unflexible formulas used only Rhoplex MC-76. These ratios were followed as per Phillips's recommendations.

For all of the filled formulations, a mixture of equal parts Type S hydrated lime, inert glass microballons (20–200 microns), and fluid coke (<0.75 mm), which was a filler and active-shrinkage compensator, were blended using a ball mill for 20 minutes to ensure good mixing. For the thickened formulations, 20

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percent Acrysol ASE-60 by volume of the dispersion formulation was added prior to the addition of any dry ingredients. Following Phillips's preliminary assumptions and recommendations, a testing program was designed to evaluate tensile bond strength of the various formulations on wood and plaster. To evaluate thermal effects on the formulations, heated assemblies were placed in an oven at 158°F (70°C) for a period of 12 hours prior to testing and were removed only when the testing equipment was fully prepared for that specific sample.

Testing-Program Methodology

Numerous protocols for adhesive testing and performance evaluation have been described for conservation applications.[8] Most authors agree that while controlled testing is an indispensable tool to quantify and communicate performance properties, tests must also reflect those essential characteristics relative to each situation in a realistic and sensitive way. The most commonly tested properties of adhesives used in conservation include bond strength in tension and shear, plasticity (modulus of elasticity), creep (cold flow), shrinkage, discoloration, acidity/alkalinity, and solubility (as an indicator of reversibility).[9] For the Drayton Hall treatments, tensile strength and elasticity were studied comparatively for six different acrylic formulations.

Materials were formulated and prepared according to Phillips's research. The decision not to vary the original formulas was based on the importance of testing the effect of the different ingredients as used elsewhere (Appendix A). Phillips identified three formulation variables based on the desired performance characteristics of the adhesive — strength and flexibility (flexible/unflexible), flow (thickened/unthickened), and shrinkage (filled/unfilled) — that could be manipulated to create different mixes suited for various situations. In addition Phillips commented on the need to use formulations with a high glass-transition temperature due to the potential of "a dangerous loss of strength by thermal softening in attic spaces where temperatures are high."[10] For Drayton Hall this issue of temperature was considered significant. Not having any artificial cooling systems, the building experiences high interior temperatures, ranging from approximately 84°F (29°C) on the first floor to over 100°F (38°C) in the attic during July.[11]

The current testing program was designed using ASTM D897-00, Standard Test Method for Tensile Properties of Adhesive Bonds, and ASTM D2095-96, Standard Test Method for Tensile Strength of Adhesives by Means of Bar and Rod Specimens. For this particular situation, however, the testing was modified to accommodate the specified substrates (Fig. 5). Mechanical tests were run on two different sets of samples. The first set was comprised of cast surrogate coupons of gypsum plaster that were used as one adherend to test the tensile strength of the various adhesive formulas on sound plaster. For the gypsum samples, ¾-inch-thick disks of plaster of paris were cast with a 2-inch diameter to ensure that enough surface area would be in contact with the adhesive to calculate its tensile strength (see Appendix B).[12]

For the second set of samples, original brown-coat samples from the ceiling were tested with the same adhesive formulations to measure their bond strength. These combinations included brown coat to brown coat, brown coat to gypsum plaster (replicating finish coat), and brown coat to wood (replicating lath). The results for each sample set were used to corroborate the observed behavior of the different adhesive formulations in both the ideal surrogate facsimile (first set) and with the actual plaster materials (second set). Although only 17 combinations were possible given the limited amount of original plaster, the results of the mechanical testing were significant, especially for the comparative results obtained with the 36 gypsum facsimiles.

In order to imitate the conditions associated with field application through small, drilled injection ports, half of the gypsum disks from set one had 5/32-inch holes drilled at the center. Spacer disks with ⅛-inch diameter were cut from Plexiglas and glued in three locations at the edge of one of the coupons to create a uniform gap for injection. Phillips determined that an unfilled formula could be used "only in voids so narrow that the absolute amount of shrinkage will be small."[13] He did not suggest a specific size for the unfilled formulas but stated that "whenever the space between the lath and plaster is greater than approximately 0.1 inch (2–3 mm), it is suggested that the filled formulation be used."[14] Based on this recommendation, gapping for the different formulations was set at 1/16 inch for the unfilled formulation and at 3/16 inch for the filled formulation. The Plexiglas spacers ensured that these gap dimensions remained uniform for all of the tested samples.

After attaching the spacers to the bottom disks, the upper disks (which contained the injection holes) were placed on top, and the two disks were taped together around the edges. Small openings were left in the tape to allow for air displacement during injection. Each set of disks was then epoxied to the surface of a 3½-inch square of plywood block ¾-inch thick, which allowed the finished assemblies to be attached to the surface of the testing apparatus. A wooden disk that allowed for the insertion of a threaded steel rod was epoxied to the top of each of the sample assemblies. This rod was fitted with a wire assembly that acted like a universal joint to limit the amount of breakage that could occur as the assemblies were being attached to the testing equipment (Fig. 5).

To apply the adhesives to each sample assembly, the mixed formulations were injected into the hole drilled in the top disk using a 14-gauge stainless-steel canula. Just prior to injection, a wetting agent was sprayed into the holes, based on Phillips's recommendations, consisting of three parts water, three parts denatured ethyl alcohol, and two parts Rhoplex MC-76. To ensure consistent wetting and complete injection for each sample, both the spray and adhesive were applied until they flowed out of the four openings in the tape. All assemblies were left to set for one week at room temperature (73°F, or 23°C).

In 1989 a small area of the Great Hall ceiling plaster approximately 30 square inches had fallen and was saved. This section was used for both the analysis of the plaster and the second set of assemblies for mechanical testing. Due to the limited amount of material available, only 17 1-inch squares were cut and tested. These limitations did not allow for a minimum of three sample cohorts

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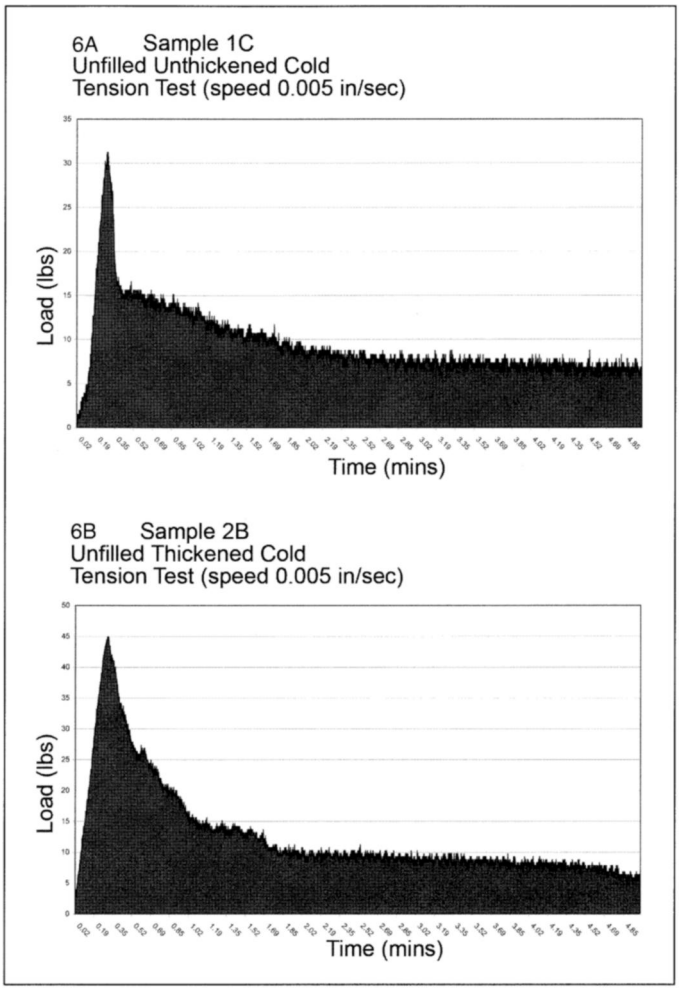

Fig. 6. Strength curves for (a) unfilled unthickened cold and (b) unfilled thickened cold formulations on surrogate plaster specimens.

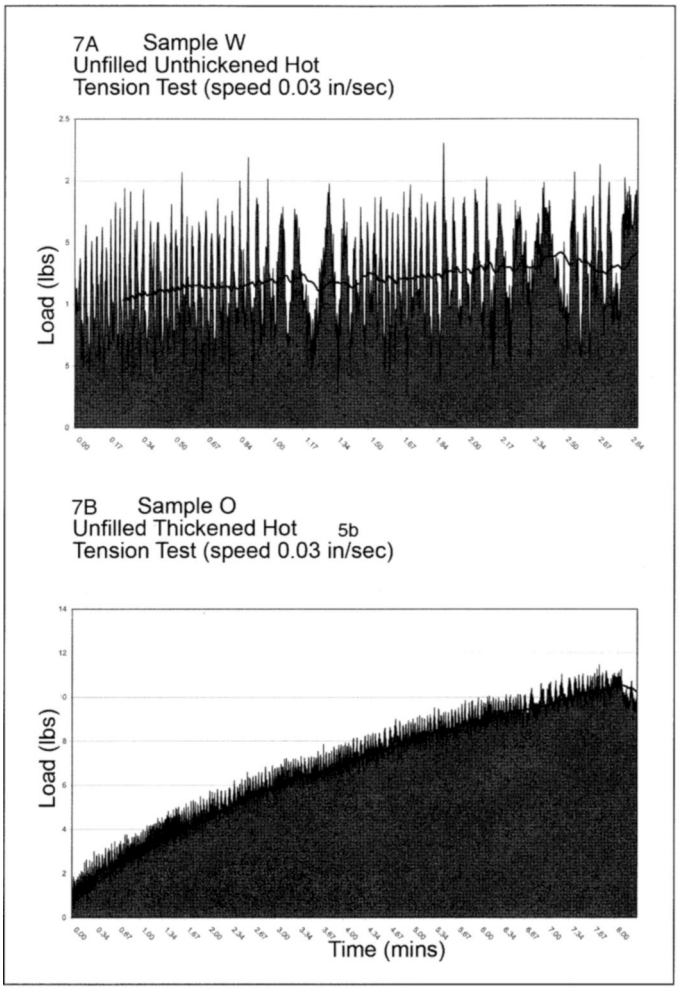

Fig. 7. Strength curves for (a) unfilled unthickened hot and (b) unfilled thickened hot formulations on surrogate plaster specimens.

to be run for each adherend combination and formulation. Since more valuable information could be gained by introducing other variables, it was decided that testing should be conducted on the three different combinations of ceiling materials that could potentially be involved in the reattachment process (wood to brown coat, brown coat to brown coat, and finish coat to brown coat). Since the original material was very limited in quantity and the samples were small, it was decided not to inject the adhesives but rather to apply them with a small palette knife just prior to assembly. This process allowed for more control of coverage to ensure a complete adhesive coating to the adherends. The same uniform gapping was set using small wooden spacers.

Prior to assembly, all original brown-coat adherends were first consolidated with a 10 percent solution (weight per volume) of Acryloid B67 in white spirits.[15] Analysis of the plaster had confirmed a high clay content, which was probably responsible for the inherent friability of the plaster. Like the gypsum assemblies, all brown-coat samples were allowed to cure for one week at room temperature prior to mechanical testing. Heat-treated samples were placed in an oven at 158°F (70°C) for 24 hours and tested upon removal.

All testing was conducted by Alexander Radin, director of the Mechanical Testing Center of the Laboratory for Research on the Structure of Matter at the University of Pennsylvania. Tests were performed on an Instron Universal Testing Machine, model 4206. This is an electro-mechanical system, which uses a special data-acquisition system called Measure, developed by National Instruments. This data-collection system is a Microsoft Excel add-in, allowing for the collection of two independent channels of data to be recorded in a spreadsheet. Channel one records the displacement of the machine, while channel two records the applied load. Per ASTM D2095-96, testing involved increasing the displacement of the top element of the machine by increasing load as the machine responded to resistance. All samples were run until the sample failed completely (as in the case of the rigid samples) or until a peak load was surpassed (as in the case of the flexible samples.) The resulting data in Excel allows for the creation of a graph that displays the load (in pounds) in relation to the time of the test (in minutes). The shape of the graph indicates the physical characteristics of the material under load while the

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height indicates the maximum load applied and the length indicates the duration of the test.

Observations on the Performance of the Facsimile Assemblies

Unfilled formulations. The most significant result of the mechanical testing was the large difference in tensile strength between all the unfilled and filled formulations, regardless of adherend material (wood or plaster). In the case of the unfilled formulas, all of the samples displayed a significantly lower tensile strength as well as a distinctive plastic response not seen in the filled formulations, which instead broke abruptly. No unfilled, unflexible formulations were tested due their poor working properties.

Unfilled flexible unthickened cold (U/Fl/Uth/C). For this set of samples the maximum resistance for two samples was 9 to 10 pounds, while the third sample showed a noticeable increase to just over 30 pounds (Fig. 6a). Close examination revealed that the adhesive had not made full surface contact with both plaster adherends in the first two specimens due to shrinkage before set. All samples, however, did display elastic behavior.

Unfilled flexible thickened cold (U/Fl/Th/C). The resistance strength for the three replicates was higher than for the unthickened formulation, measured at 45, 50, and 62 pounds, respectively (Fig. 6b). Although these results might suggest that the thickened formula may be stronger than the unthickened, the observed adhesive contact in these samples was considerably greater in surface area than for the unthickened samples, providing higher apparent strength. Thus it seems that the thickener may have helped to improve surface contact by reducing the shrinkage during set.

Unfilled flexible unthickened hot (U/Fl/Uth/H). In contrast to the cold specimens of the same formulation, the heated specimens show a significant reduction in overall strength (Fig. 7a). The maximum resistance strength achieved was 2.2 pounds for the first sample and 4.0 pounds for the second. Although the graphs in both cases illustrate that the specimens exhibited little resistance to load, both samples displayed a low increase in resistance throughout the test. In both cases the displacement was large, with limited signs of breakage, indicating high plasticity.

Unfilled flexible thickened hot (U/Fl/Th/H). These two assemblies displayed lower resistance strength to heat by 60 to 70 percent when compared to the same samples cold (Fig. 7b). Once the unfilled formulas (which did not break) were removed from the testing equipment, they were allowed to relax. All samples had a tendency to rebound, approaching their original set positions, thus exhibiting elasticity. In the case of one of the filled, heated formulas, the sample that had withstood a maximum load of 11 pounds was returned to the oven for a period of 30 minutes and then subjected to the same tension test. The graph of this second test showed a similar pattern of resistance to applied load that was seen in the first graph, with a reduction of maximum load to just over 9 pounds.

Filled formulations. In most cases the filled formulas exhibited complete surface-to-surface adhesion, suggesting that the material bonded well to the substrate.

Filled unthickened flexible cold (F/Uth/Fl/C). All three specimens tested had a considerable increase in maximum load capacity when compared with the unfilled formulas (Fig. 8a). Where the average maximum load capacity of the unfilled formulas was 16 pounds, the average maximum load capacity for the filled formula was 160 pounds, or more than ten times the resistance capacity to applied load. Additionally the graphs show a significant difference in physical response with no significant plastic response. For all samples in this test group displacement was limited and failure was complete and abrupt.

Filled unthickened unflexible cold (F/Uth/Ufl/C). One of the primary goals of this testing program was to determine the extent of plasticity imparted to the flexible formulations with Rhoplex 1950. When the samples of the flexible, filled formula are compared with the unflexible, filled formula, the shape of the graph is very similar (Fig. 8b). A constant slope and abrupt break at the yield point in both cases suggests limited flexibility like that found in the unflexible formulas. The most significant difference is the overall tensile strength. For the flexible formulas the average load capacity was 160 pounds, while the unflexible formulation averaged 230 pounds (and in one case reached 250 pounds), suggesting a significant increase in overall strength, as expected.

Filled thickened flexible cold (F/Th/Fl/C). The most notable result of the addition of the thickener in this case is the reduction of overall strength from an average of 160 pounds to an average of 116 pounds (Fig. 9a). Based on these lower numbers it is likely that the addition of the thickener is reducing the strength. Acrysol ASE-60 is designed to help increase viscosity without greatly reducing injectability. As injectability and strength are both important properties, this could be a significant consideration when higher strength is needed. The graphs in this case suggest the same failure mode as seen in the unthickened, filled formulations just discussed. Failure was complete and abrupt. Once again, the constant slope of the graph suggests limited elasticity.

Filled thickened unflexible cold (F/Th/Ufl/C). These three samples revealed a similar pattern between the thickened and unthickened formulations for the unflexible formulation as observed for the two flexible mixtures (Fig. 9b). While the graphs again show no clear sign of elasticity, the thickened formulations display a reduction in the maximum load capacity before failure. In the case of the unthickened formula, the average maximum load capacity was 230 pounds, while the average maximum load capacity of this thickened formulation was 196 pounds. It is likely that with an increase of thickener, the overall strength of the formulation is reduced.

Filled unthickened flexible hot (F/Uth/Fl/H). As was observed with the unfilled formulations, the introduction of heat as a variable had a significant impact on all of the filled formulations in similar ways (Fig. 10a). The two specimens in this group exhibited a maximum load capacity of only 39 and 57 pounds, respectively. When compared with the un-

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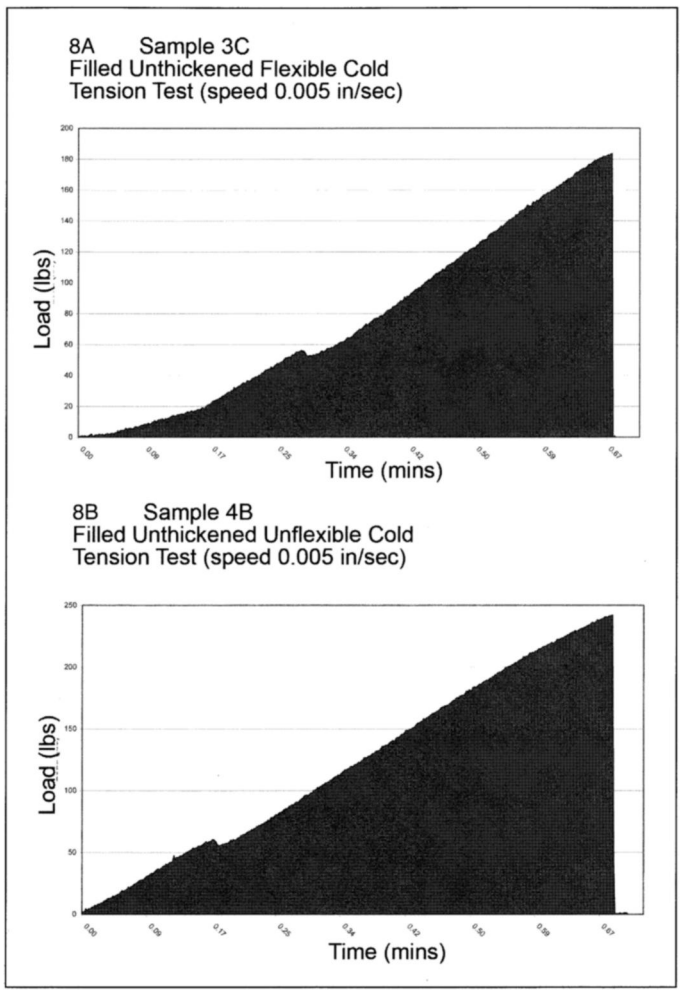

Fig. 8. Strength curves for (a) filled unthickened flexible cold and (b) filled unthickened unflexible cold formulations on surrogate plaster specimens.

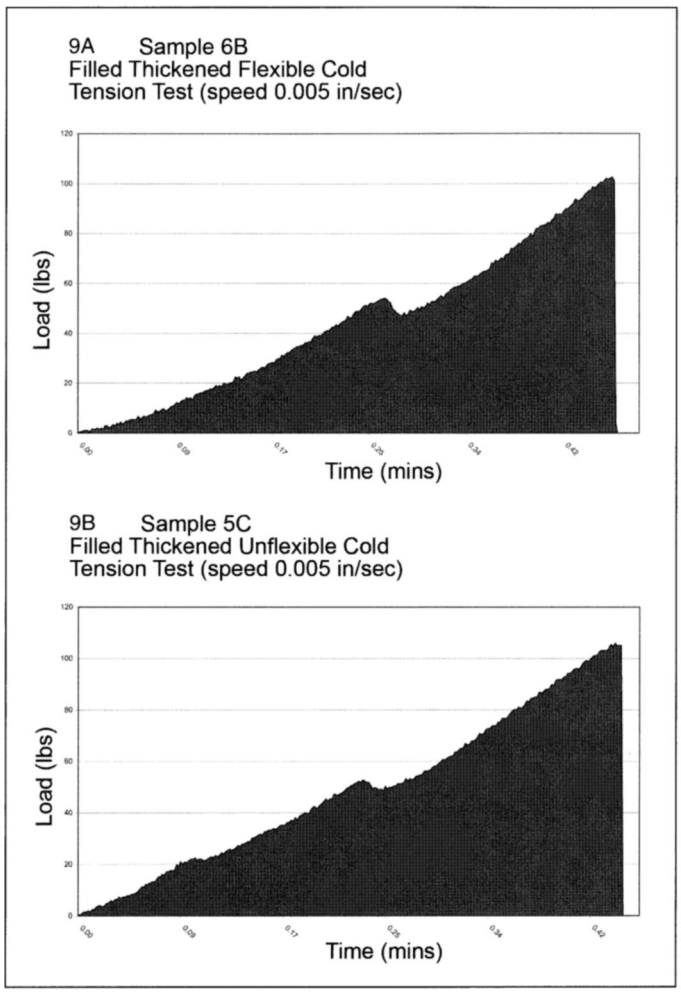

Fig. 9. Strength curves for (a) filled thickened flexible cold and (b) filled thickened unflexible cold formulations on surrogate plaster specimens.

heated formulas with similar variables (i.e., filled flexible unthickened cold), the maximum load capacity for the heated samples was significantly reduced, showing a reduction in strength of more than 60 percent. Perhaps more significant is the plastic response when heated. Unfortunately, the rate of failure in the heated specimens appears to be quite high. Once the graph has reached its peak, the slope becomes quite steep. Eventually this slope becomes more shallow, suggesting that the failure, although significant, is not complete. Upon close examination of the heated-set formula, the texture is similar to that of stiff toffee. Cold specimens are very hard, while the heated formulas remain elastic.

Filled unthickened unflexible hot (F/Uth/UFl/H). As seen in the results of the last two tests, both specimens had a lower overall maximum load capacity as a result of temperature increase (Fig. 10b). In the case of the unheated formulas (filled unflexible thickened cold), the average maximum load capacity for the three specimens was 230 pounds. For the heated specimens that number was reduced to 55 and 100 pounds.

Filled thickened flexible hot (F/Th/Fl/H). Once again a noticeable reduction in strength was seen as a result of the introduction of heat (Fig. 11a). For the two specimens tested, both were below 35 pounds of maximum load capacity, and in both cases the response to increased load as seen in the graph suggests that the sample had become weaker and less brittle. Both graphs display a curve at the top suggesting that failure is not catastrophic followed by a steep downward slope and then a much shallower curve. This shallower curve, which was seen in all of the heated, filled samples, suggests that the failure is not complete and that as the displacement is increased, the failure continues but at a greatly reduced rate, as seen just after the peak load is achieved.

Filled thickened unflexible hot (F/Th/Ufl/H). Again, the lower overall strength is observed when compared to the matching cold formulation, and the response to failure is the same as seen in the other filled, heated samples (Fig. 11b). The constant slope at the bottom suggests that elasticity is limited; however, the curve at the top again shows that failure is not sudden. The elastic consistency of all of these heated, filled formulations is similar. The performance of all the formulations under heat show significantly low tensile strength and high plasticity,

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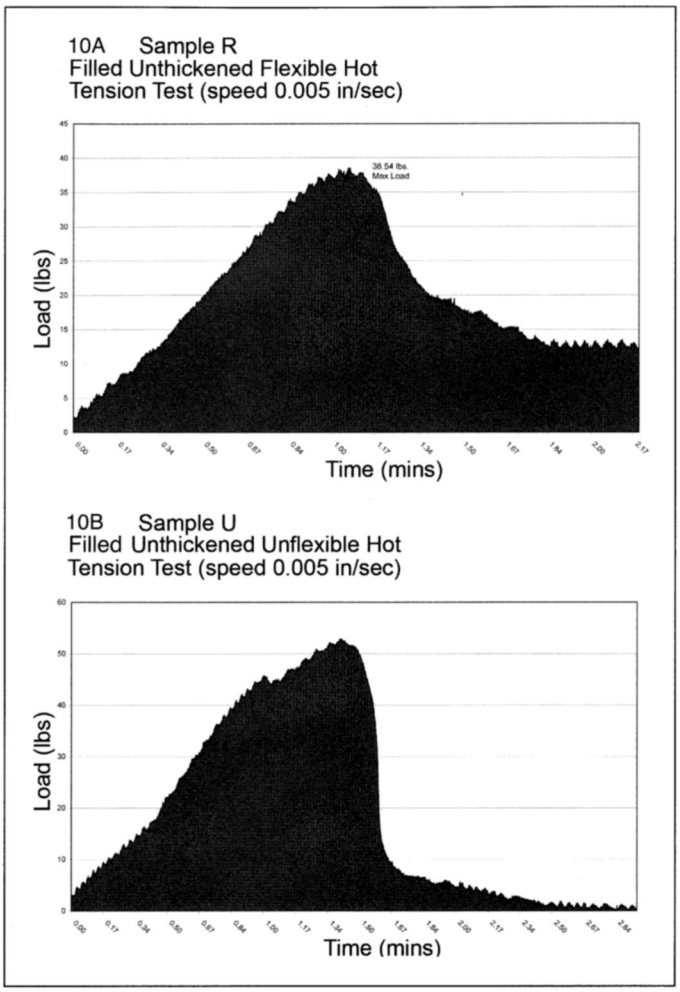

Fig. 10. Strength curves for (a) filled unthickened flexible hot and (b) filled unthickened unflexible hot formulations on surrogate plaster specimens.

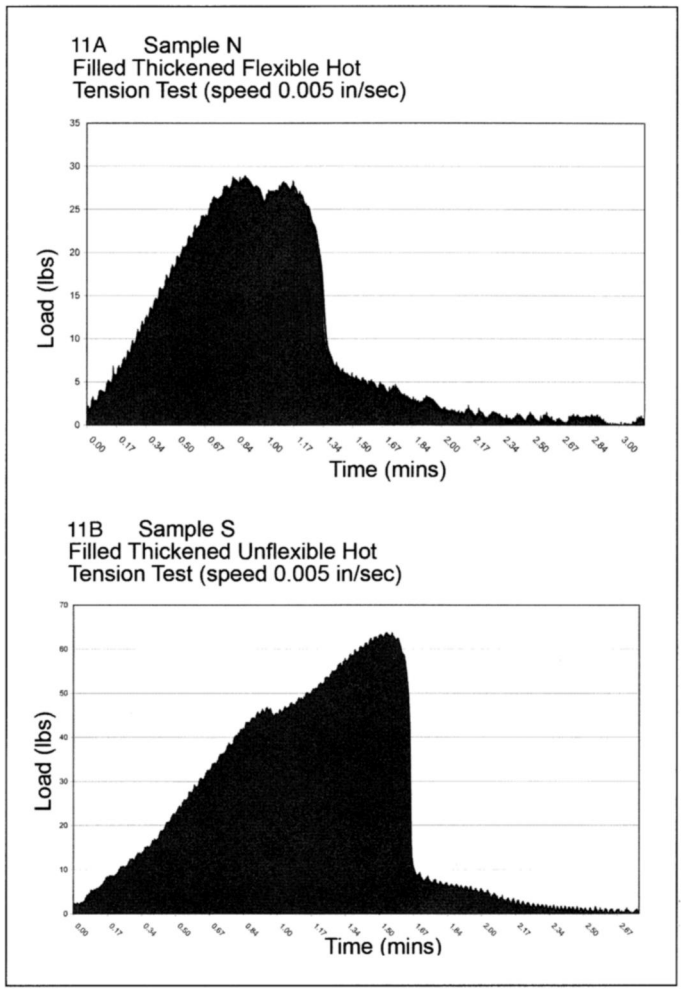

Fig. 11. Strength curves for (a) filled thickened flexible hot and (b) filled thickened unflexible hot formulations on surrogate plaster specimens.

regardless of the resins used or the presence of fillers and thickeners.

Observations on the Original Plaster Assemblies' Performance

The results of the mechanical tests performed on the Drayton Hall plaster samples were similar to those of the gypsum surrogates. Testing showed that while the flexible and unflexible formulations possessed sufficient bond strength for the reattachment of the plaster to itself and to the wooden lath, they differed significantly depending on whether they were filled or unfilled. Both formulations exhibited good and complete adhesion to the adherends and a bond strength greater than the cohesive strength of the consolidated brown coat. Only the filled, flexible, thickened formulation proved to be the closest in tensile strength to the consolidated original brown coat and therefore the most compatible in mechanical properties. In most cases the comparison of one combination of bonded adherends to another using the same formula resulted in similar performance.

Generalizations Based on Testing

The following conclusions can be drawn from the mechanical testing program on the surrogate and original plaster samples.

All the unflexible formulations displayed greater tensile strength than the flexible formulations. This result is to be expected, given the original intended properties of the preselected acrylic resins.

The flexible, filled formulation displayed little difference in plasticity compared to the unflexible, filled formulation, as well as a lower tensile strength. While fillers are necessary to control shrinkage, they also significantly modify the modulus of elasticity and appear to negate the elastomeric properties of the Rhoplex 1950.

The filled formulations had considerably higher tensile strength than the same unfilled formulations. The increase in strength afforded by these and other fillers (e.g., fumed silica) is reported in the adhesive literature. However, their dramatic effect on stiffness (modulus of elasticity) and strength was not considered with respect to Phillips's designated flexible formulations.[16]

The thickened formulations generally exhibited lower tensile strength than the

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same unthickened formulations. This phenomenon is most likely due to the percent of resin solids available in a given volume of grout. Nevertheless, the thickener appears to improve bond strength in the unfilled formulations by increasing surface contact of the adhesive to the adherend and by reducing shrinkage. Any gap greater than 1/16 inch is too great for the unfilled, unthickened formulation, due to shrinkage.

The heated samples all displayed lower tensile strength and greater plasticity and elasticity than the samples tested at room temperature, due to the thermal response of the acrylic resins. This factor is important for the Drayton Hall project, as the house is not climate controlled, and the interior temperatures of the upper rooms and attic can easily reach above 104°F (40°C) in the summer months. While increased plastic/elastic behavior at higher temperatures might be desirable to counteract thermal movement of the ceiling, it could also lead to creep of the formulations, as well as possible deformation and detachment of the ceiling plaster if the adhesive was used extensively and as the sole means of reattachment.

Treatment Program

Complete reattachment. The first areas of the ceiling to be treated were two large, unstable sections where damaged plaster had been completely detached exposing the lath beneath. These areas allowed for the use of the unfilled mixture since the plaster being reinstalled was in direct contact with the surface of the lath. In order to treat these areas, loose plaster fragments that showed signs of imminent failure were removed as well. The lathing itself was then thoroughly cleaned using a stiff brush to remove dust and debris, at which point the lath was carefully inspected and the visible impact of the 1978 treatment studied. No lath reattachment with noncorrosive fasteners was required. Plaster fragments were carefully laid out and numbered for easy installation.

After the lathing was brushed clean, a 10 percent solution of Acryloid B-67 dissolved in mineral spirits was applied over the exposed lathing. Each fragment of plaster was also thoroughly brushed clean and the back consolidated with B-67 in order to increase the cohesive strength of the friable brown coat. Following the consolidation of each fragment, which was allowed to dry overnight, a thickened coat of the unfilled, flexible acrylic mixture was brushed onto both the backside of the plaster and the underside of the wood lath. The thickener for the treatment was created by adding a small amount of ammonia to Acrysol ASE-60, which produced a clear, inert gel similar in consistency to pudding. This gel could be added as needed to increase the viscosity and tack of the mixture. Because all of the work on the ceiling was conducted from below, the thickener was extremely valuable by helping to limit the amount of dripping and sagging of adhesive caused by gravity.

With both surfaces coated, each loose piece of plaster was then installed in its original location and supported using a telescoping leg with soft padding on the end. These supports, reused from the earlier temporary stabilization, were left in place overnight, allowing the repair to set. Once all of the fragments were well adhered and the supports removed, all of the cracks around the newly installed fragments were infilled (see below).[17]

Preconsolidation and injection grouting. The next phase in the treatment involved injection of the filled, flexible acrylic dispersion formulations to reattach areas of the ceiling that were identified as detached and in some cases deformed but were still in place. Once cracks and their adjacent areas had been identified for injection, holes were drilled at an interval of approximately ½ inch using a 7/64-inch drill bit. For each crack, drilling was begun in the center of designated lengths instead of at the ends. This procedure ensured that only truly detached areas were injected, rather than the entire crack. As each consecutive hole was drilled in a given direction along a crack, the amount of space between the plaster and the lathing was monitored by noting the resistance of the drill as it moved from the plaster, through the gap, to the lathing and poured plaster above. As the drilling progressed along the length of the crack, this gapping continued to shrink until it disappeared completely. When the gapping ended, the drilling was stopped and then reinitiated from the first hole drilled, traveling in the opposite direction along the crack.

As one team member carried out the drilling, the other member cleared dust and debris with compressed air and consolidated the friable brown coat with a 10 percent solution of Acryloid B-67 and mineral spirits. During the treatment-testing phase, mineral spirits had been identified as the only solvent (including water) that did not cause staining of the ceiling's whitewashed surface, thus necessitating the use of B-67. In order to introduce the consolidant to the voids, an aerosol was created using a pressurized bottle. Attached to the tip of this bottle was a 6-inch flexible extension tube, which could be inserted into the void through the drilled holes. The flexibility in the tube allowed the introduction of the consolidant in all directions in an attempt to maximize the coverage. By using an aerosol, it was possible to consolidate with a lower controlled volume at higher pressure, thus increasing the range of coverage and reducing the chances of oversaturation. Once these areas were consolidated, they were allowed to dry overnight. Holes were then drilled in phases in order to ensure the completion of treatment during the available time period. The first set of holes drilled for treatment was in the most threatened areas of the ceiling. These holes were drilled and consolidated on the first day, followed the next day by the injection of the grout.

Due to the size of the voids encountered during the drilling of the injection ports and supported by the results of the mechanical testing, all of the injected repairs were carried out using the filled, flexible, thickened formula. All acrylic-dispersion mixes were created just prior to injection and were used for no more than one hour, at which point any remaining mix was discarded and a new batch created. Due to backflow from predrilled holes under injection pressure, the acrylic thickener was added until the final mix achieved a gel-like consistency. Although material was still ejected out through the drilled ports, its higher viscosity meant that the ejected material could be removed easily and quickly

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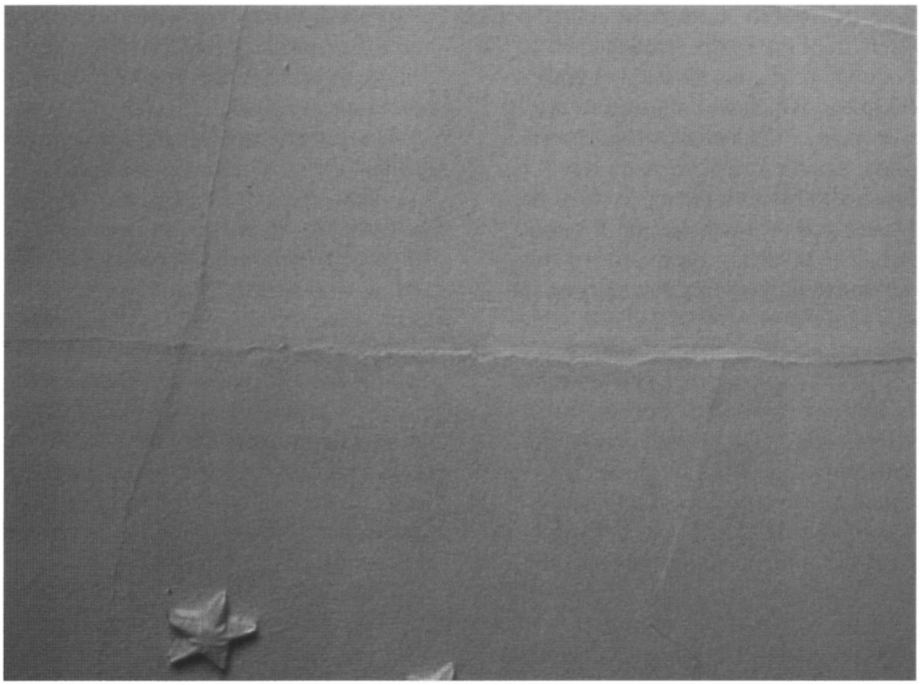

Fig. 12. Post-injection fill compensation, which stabilizes crack edges and will help show any movement of the ceiling.

with a small palette knife without staining the surrounding plaster.

Injection was done using a 20cc veterinary syringe with a stainless-steel canula. Obviously the smaller the drilled port, the less apparent the fills would be from the floor. The final choice of a 2-inch-long metal canula with a 3/32-inch diameter was based on the size of the flexible tube used for the consolidant injection. Injections conducted near one of the areas of exposed lath allowed for a cross-sectional view of the process, and the evidence showed that the mix had all of the desired physical properties, including low shrinkage and good flow under pressure (i.e., thixotropy).

Just prior to the actual injection of the filled dispersion grout, each hole was wetted with a 5 percent solution of the unfilled adhesive in order to improve bonding. This process presented problems similar to those that occurred during consolidation, i.e., control of the liquid was often difficult, necessitating application with a spray bottle.

Three separate phases of drilling, consolidation, wetting, and injecting adhesive were carried out on the surface of the ceiling, with each consecutive phase addressing identified areas of lesser concern. In the end more than 1,000 holes were drilled and injected. Based on the weight of each material and the overall amount of material injected into the ceiling, it was determined that no more than five pounds of dry weight was added to the ceiling with this reattachment method.

All injection holes were filled with a commercial lightweight jointing compound, which was mixed with equal parts of microballoons to make a drier, weaker fill and one that closely matched the color and texture of the existing whitewashed finish plaster.[18] In addition to the holes, several of the larger cracks were filled as well in an attempt to reduce their visual impact from below and to provide additional support to the crack edges (Fig. 12). The advantage of these soft, slightly elastic filled cracks is that they can now act as "telltales," helping to show movement resulting from the introduction of live load to the second floor above the Great Hall for the first time in more than 10 years. Should these fills crack over time from plaster movement, they can easily be replaced. Finally, loose and previously removed cast ceiling ornaments were reattached with the unfilled adhesive formula.

Conclusions

Prior to Morgan Phillips's research, the stabilization of detached plaster-and-lath ceilings relied on the nontraditional use of traditional materials and methods. While often effective in stabilizing detached plaster ceilings either through localized key reattachment or by circumventing the entire lath support system and introducing a new attachment method to the primary framing, these systems were invasive and added considerable weight to the ceiling. In addition, they were largely irreversible and encumbered future retreatment. Phillips's injection formulations, based on acrylic dispersions, were designed to be low-impact through their specificity of application and to provide versatility in the performance characteristics required for each unique situation: strength, flexibility, viscosity, thixotropy, and gap-filling (shrinkage control).

This recent mechanical testing of Phillips's formulations has provided for the first time quantitative, comparative data on their tensile strength, elasticity, and thermal response. While viscosity, injectability, and shrinkage were not measured, their manipulation and intended effects as a function of the fillers and thickeners recommended by Phillips are clearly observable. The mechanical testing has revealed the significant effect these additives have on the tensile strength and especially on the stiffness of the formulations, a critical property for many reattachment situations. Additional study is needed on the individual effects, if any, of the different recommended fillers (lime, whiting, microballoons, and fluid coke), as well as other filler choices (e.g., fumed silica) and resin combinations and additional mechanical tests, such as creep.

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Notes

1. The major relevant conservation studies, in chronological order, are as follows. Robert A. Shoolbred, *Report on the Structural Analysis of Drayton Hall for the National Trust for Historic Preservation*, March 5, 1977. John G. Waite, *An Evaluation of the Condition and Preservation Potential of Decorative Plaster Ceilings at Drayton Hall, Charleston, South Carolina*, Grant No. 90-75-00133-00 Heritage Conservation and Recreation Service Development Project Completion Report, 1977. Charles Edwin Chase and Kevin Murphy, *Drayton Hall: Architectural and Documentary Research Report*, 1988. National Trust for Historic Preservation Colloquium held at Drayton Hall, April 27- 29, 1990, videotapes 1-3 recorded by John Kidder. Frank G. Matero et al., *Documentation and Conditions Survey, Great Hall Ceiling, Drayton Hall, South Carolina*, December 6, 1990. Ford Farewell Mills and Gatsch Architects, "Architectural Engineering and Conservation Study of Drayton Hall: Technical Report" (unpublished report, 1998), vii-1.

2. Frank G. Matero, John Hinchman, Dana Tomlin, and Kyu-Bong Song, "A GIS Assessment of the Great Hall Ceiling at Drayton Hall, Charleston," *APT Bulletin* 34, no. 2-3 (2003): 25-36.

3. This work was undertaken by Robert Silman Associates, New York, N.Y. (structural engineering); Architectural Conservation Laboratory, University of Pennsylvania, Philadelphia (plaster conservation); and Richard Marks Restorations, Charleston, S.C. (structural wood repair).

4. The 1998 technical report by Ford Farewell Mills and Gatsch included recommendations by George Fore for the detachment and reattachment of discreet plaster panels under the hearth area; reattachment of detached areas in situ with blind adhesive grouting or pinning from above; and stabilization with exposed hanger supports.

5. This trend in research is due to the common problem of detachment of mural paintings on masonry walls and vaulted ceilings.

6. William Millar, *Plastering Plain and Decorative*, 4th ed., ed. George P. Bankert (New York: Dodd, Mead and Co., 1927), 272.

7. Morgan W. Phillips, "Experiences in the Use of Acrylic Plaster Adhesives" in *Case Studies in the Conservation of Stone and Wall Paintings. Preprints of the Contributions to the Bologna Congress , 21-26 September 1986*, ed. N. S. Brommelle and P. Smith, 34-37 (London: International Institute for Conservation of Historic and Artistic Works, 1986). Morgan W. Phillips, "Adhesives for the Reattachment of Loose Plaster," *APT Bulletin* 12, no. 2 (1980): 37-63.

8. Gustav A. Berger and Harold I. Zeliger, "The Procedure of Developing an Adhesive for Paintings: The Importance of Valid Tests," 13-17, and Susan Bradley, "Strength Testing of Adhesives and Consolidants for Conservation Purposes," 22-25, in *Adhesives and Consolidants, Preprints of the Contributions to the Paris Congress, 2-8 September 1984*, ed. N. S. Brommelle et al. (London: International Institute for Conservation of Historic and Artistic Works, 1984). Jerry Podany, Kathleen M. Garland, William R. Freeman, and Joe Rogers, "Paraloid B-72 as a Structural Adhesive and as a Barrier within Structural and Adhesive Bonds: Evaluations of Strength and Reversibility," *The Journal of the American Institute for Conservation* 40, no. 1 (2001): 15-33.

9. ASTM D907-05, Standard Terminology of Adhesives. Jane L. Down, "Adhesive Formulations Testing at the Canadian Conservation Institute, Past and Future," *Studies in Conservation* 41, no. 1 (1996): 19-44.

10. Morgan W. Phillips, "Adhesives for the Reattachment of Loose Plaster," 60.

11. Ford Farewell Mills and Gatsch, vi-20.

12. Tensile strength is reported in the text and in the graphs as the actual recorded resistant force recorded during testing. This force can be calculated as tensile strength or the maximum tensile stress that the adhesive is capable of sustaining calculated from the maximum load applied perpendicular to the joint divided by the original cross-sectional area of the joint in Table 1.

13. Phillips, "Reattachment of Loose Plaster," 49.

14. Ibid.

15. Of the various solvents tested, including water, all but white spirits induced staining on the plaster ceiling surface. This was attributed to an unknown soluble fraction in the brown coat. For this reason, Acryloid B-67 became the consolidant of choice.

16. Gregory S. Byrne, "Adhesive Formulations Manipulated by the Addition of Fumed Colloidal Silica," in *Adhesives and Consolidants*, 78-80.

17. Although the adhesion in the hearth area was successful, one difficulty resulting from the 1978 treatment was the inability to position the reapplied plaster in a uniform plane with the rest of the ceiling. Prior to the 1978 treatment the lathing in this area had become loose — possibly a result of corroded lath nails associated with water leaking through the roof — and had pulled away from the surface of the joist to which it had been attached. The 1978 treatment of the ceiling from above caused the gaps between the lathing and the joists to become filled with plaster of paris that, once set, eliminated the possibility of this lathing being renailed in plane with the other laths. This problem was then telegraphed outward to the newly reattached portions of plaster, resulting in an uneven surface.

18. Cross-sectional analysis of the ceiling reveals a calcium carbonate wash applied to the finish plaster. This surface most likely dates to the original ceiling or a late-nineteenth-century repainting. This finish is stained from dark fungal biogrowth and requires cleaning that was beyond the scope of this project. Surface cleaning of the cracks prior to filling resulted in cleaned areas bordering the cracks.

Appendix A: Sites Treated with Morgan Phillips's Plaster-Stabilization Method

1. Lockwood-Mathews Mansion Museum (c.1870), Norwalk, Conn.

2. Southport Congregational Church (c.1870), Southport, Conn.

3. Goodwood Museum and Gardens (c.1839), Tallahassee, Fla.

4. Demosthenian Hall (c.1847), University of Georgia, Athens, Ga.

5. Hay House Museum (1880s), Macon, Ga.

6. Owens-Thomas House Museum (1819), Savannah, Ga.

7. John Heavey House (c.1845), Leavenworth, Kans.

8. James Brice House (c.1760), Annapolis, Md.

9. Chase-Lloyd House (c.1769), Annapolis, Md.

10. Rose Hill (c.1840), Earleville, Md.

11. Massachusetts State House (1797), Boston, Mass.

12. St. John the Evangelist Church (1880s), Clinton, Mass.

13. Orchard House (1857), Concord, Mass.

14. Thomas Gardner II House (c.1709), Nantucket, Mass.

15. Chesterwood (c.1902), Stockbridge, Mass.

16. First Parish of Sudberry (c.1793), Sudberry, Mass.

17. St. Paul's School, Old Chapel (1867), Concord, N.H.

18. Tilton School (1880s), Tilton, N.H.

19. New Jersey State Capitol (1872), Trenton, N.J.

20. Yiddish Arts Theatre (c.1823), New York, N.Y.

21. First Presbyterian Church (c.1844), Sag Harbor, N.Y.

22. The Grange Estate (c.1700), Havertown, Pa.

23. Solitude (c.1784), Philadelphia, Pa.

24. Chorus of Westerly (c.1891), Westerly, R.I.

25. Drayton Hall (c.1743), Charleston, S.C.

26. Franklin-Adams House (c.1892), Deadwood, S.D.

27. Park-McCullough House (c.1865), Bennington, Vt.

28. Vermont State Capitol (c.1850), Montpelier, Vt.

29. Arlington House, The Custis-Lee Mansion (c.1803), Arlington, Va.

30. Mt. Vernon (1756), Mt. Vernon, Va.

31. St. Francis Xavier Church (1860s), Parkersburg, W.Va.

Prepared by David Flaherty and Andrew Ladygo

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Appendix B: Tensile Strength (ASTM D2095-96 modified)

Sample No.	Sample ID	Addition of Fillers	Addition of Rhoplex 1950 for Flexibility	Addition of Acrysol ASE-60 as a Thickener	Addition of Heat	Applied Load Under Tension (lbs)	Tensile Strength (lbs./in^2)
x	U/Fl/Uth/H	No	Yes	No	Yes	4.15	1.32
w	U/Fl/Uth/H	No	Yes	No	Yes	2.3	0.73
v	F/Ufl/Uth/H	Yes	No	No	Yes	104.04	33.13
u	F/Ufl/Uth/H	Yes	No	No	Yes	52.89	16.84
t	F/Ufl/Th/H	Yes	No	Yes	Yes	93.14	29.66
s	F/Ufl/Th/H	Yes	No	Yes	Yes	63.7	20.28
r	F/Fl/Uth/H	Yes	Yes	No	Yes	38.54	12.27
q	F/Fl/Th/H	Yes	Yes	Yes	Yes	34.87	11.1
p	F/Fl/Uth/H	Yes	Yes	No	Yes	56.71	18.06
o	U/Fl/Th/C	No	Yes	Yes	No	11.45	3.65
n	F/Fl/Th/H	Yes	Yes	Yes	Yes	no data	no data
m	U/Fl/Th/C	No	Yes	Yes	No	13.02	4.14
6c	F/Fl/Th/C	Yes	Yes	Yes	No	162.1	51.62
6b	F/Fl/Th/C	Yes	Yes	Yes	No	102.54	32.66
6a	F/Fl/Th/C	Yes	Yes	Yes	No	82.03	26.12
5c	F/Ufl/Th/C	Yes	No	Yes	No	105.96	33.74
5b	F/Ufl/Th/C	Yes	No	Yes	No	215.33	68.58
5a	F/Ufl/Th/C	Yes	No	Yes	No	229	72.93
4c	F/Ufl/Uth/C	Yes	No	No	No	254.88	81.17
4b	F/Ufl/Uth/C	Yes	No	No	No	242.19	77.13
4a	F/Ufl/Uth/C	Yes	No	No	No	201.66	64.22
3c	F/Fl/Uth/C	Yes	Yes	No	No	183.59	58.48
3b	F/Fl/Uth/C	Yes	Yes	No	No	170.9	54.43
3a	F/Fl/Uth/C	Yes	Yes	No	No	117.19	37.32
2c	U/Fl/Th/C	No	Yes	Yes	No	23.93	7.62
2b	U/Fl/Th/C	No	Yes	Yes	No	44.92	14.3
2a	U/Fl/Th/C	No	Yes	Yes	No	62.99	20.06
1c	U/Fl/Uth/C	No	Yes	No	No	30.27	9.64
1b	U/Fl/Uth/C	No	Yes	No	No	8.78	2.8
1a	U/Fl/Uth/C	No	Yes	No	No	no data	no data
		U=Unfilled F=Filled	Ufl=Unflexible Fl=Flexible	Uth=Unthickened Th=Thickened	H=Hot C=Cold		

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