

ASSESSMENT AND ANALYSIS OF THE PLASTER EXHIBIT HALL CEILING  
AT THE WAGNER FREE INSTITUTE OF SCIENCE, PHILADELPHIA, PA

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A THESIS

in

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Figure 1: Exhibit Hall, 2000. Photo by Joseph Elliot for the Historic American Building Survey; HABS PA,51-PHILA,751-15.

## 1.0 Introduction

In December of 2003, a portion of the plaster Exhibit Hall ceiling at the Wagner Free Institute of Science fell two stories, causing concern as to the stability of the remaining plaster. Replacement of the entire plaster ceiling was suggested as a response to the fallen piece and the extent of cracking.

While plaster, as a finish material, is often considered replaceable and may not be considered a high priority for conservation, the Exhibit Hall ceiling is historically significant and worth preserving. For a site of historic significance

such as the Wagner, total replacement should only be considered if the ceiling is in imminent danger of falling and if the current conditions cannot be successfully mitigated by more sensitive conservation methods such as reattachment.

In 2007, an assessment of the problem was undertaken by Building Conservation Associates, Inc. in conjunction with summer interns employed by the University of Pennsylvania's Architectural Conservation Laboratory. Visual observations do reveal that the plaster has experienced severe cracking and staining, but the ceiling appears to be sound and is not causing stress to the rest of the building. There has not been any additional loss since 2003. The truss system was deemed structurally sufficient by a structural engineer, and repairs only to the masonry walls were recommended as preventative maintenance. The assessment employed traditional diagnostic methods of assessing damage as well as Geographic Information Systems (GIS) analyses tools to determine the extent of damage, document the current conditions, and develop recommendations regarding treatment or replacement of the Exhibit Hall ceiling. A report on the observations and recommendations of this study was issued in January of 2008.

There are two objectives for this thesis: examination of the general utility of GIS as a diagnostic tool for the conservation field and exploration of the cause and effect relationship of the cracking plaster of the Wagner ceiling with the primary goal being preservation of the original fabric wherever possible. In order

to better understand these relationships, a comprehensive review of the available information about the plaster ceiling was critical to the research and has also proven critical for better understanding of GIS as a diagnostic tool. GIS, while powerful, is one of only several tools necessary to execute a comprehensive and hopefully complete assessment of the plaster and its associated conditions of the ceiling at the Wagner Free Institute of Science.





Figure 2: Wagner Free Institute of Science. From *Annual Announce*, 1911.

## 2.0 The Wagner Free Institute of Science

The Wagner Free Institute of Science was established in 1855 by the amateur scientist, William Wagner, to provide free lectures for adults on scientific topics. Wagner first began offering lectures in 1847 at his home before moving to a larger space at the Municipal Hall near Thirteenth and Spring Garden Streets in 1855.<sup>1</sup> The need for a larger building where Wagner could both offer lectures and store his growing collection of scientific specimens soon became apparent. Planning for the construction of the current building began in 1859 with its

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<sup>1</sup> *Wagner Free Institute of Science, Annual Announcement*. Philadelphia, 1911, 3.

opening just after the end of the Civil War, in 1865. The dual function of the building as lecture hall and museum space continues today.

## ***2.1 Building History***

John McArthur, a well-known institutional architect in Philadelphia who is best known for his design of Philadelphia's City Hall, was selected to design the Wagner, though Wagner had a strong enough influence on the plan to be called its designer by the local press.<sup>2</sup> The building design is based on a classical temple, with symmetrically placed pilasters and pedimented gables on the north and south elevations that conceal a barrel vault roof.<sup>3</sup> Although the building was opened to the public in 1865, many of the details of the building were left unfinished. Little additional work was done on the building until after Wagner's death in 1885.

The building has experienced three major construction campaigns in its history.<sup>4</sup> The first was the construction of the main building, the two-story structure that houses the lecture and exhibit halls. The second campaign in the 1880s entailed extensive remodeling of the interior spaces and some exterior finish work. The third major campaign was the addition of the library wing to the west side, constructed in 1901, which provided a separate space for the Philadelphia Free Library which had been operating out of the main building

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<sup>2</sup> "The Wagner Free Institute." *Philadelphia Press*, 25 October 1860.

<sup>3</sup> Eugene Bolt and Susan Glassman. National Historic Landmark Nomination, 4 April 1989, section 7, 2.

since 1892.<sup>5</sup> In addition to the three major campaigns, a small laboratory addition was constructed along the west side of the building. The laboratory was completed in 1868, shortly after construction on the main building was complete.<sup>6</sup>

Since the construction was not fully completed at the time of its opening, the major renovation campaigns in the 1880s completed many of the unfinished projects inside the building. A large sum of money left to the institution by Wagner upon his death in 1885 funded the renovation.<sup>7</sup> The firm of Collins and Autenrieth were engaged to design the alterations. Many changes occurred during this period, including the complete stuccoing of the exterior, installation of Queen Anne sashes in the windows, and the widespread installation of beaded board wainscoting and trim.<sup>8</sup> In addition, the Trustees put in a steam heating system, added plumbing and improved drainage.<sup>9</sup> The architects also designed and installed exhibit cases and cabinets for the Exhibit Hall. These are still extant in the museum today and provide an organized means for displaying Wagner's extensive specimen collection. It was during these renovations that the

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<sup>4</sup> Bolt, section 7, 1.

<sup>5</sup> Bolt, section 8, 6.

<sup>6</sup> Jacobs, James A. Historic American Buildings Survey, Wagner Free Institute of Science. HABS no. PA 6667 (2000), 7.

<sup>7</sup> Jacobs, pg. 9

<sup>8</sup> Bolt, section 7, pg. 3

<sup>9</sup> Building Improvements, 1885-1891. ARC 91-035, Wagner Free Institute of Science Archives.

current plaster ceiling was installed in the Exhibit Hall. The plaster still exists today, mostly untouched, with only one coat of paint.<sup>10</sup>

## *2.1 Preservation Philosophy*

In 1989, the Wagner Free Institute of Science was designated a National Historic Landmark. Part of the argument in favor of Landmark status was the amazing state of preservation inside the building.<sup>11</sup> Not only is the building being used as its original function, but the structure has remained largely untouched since the early 20th century. The display cases organized by renowned paleontologist Joseph Leidy, who became the chair of academic programs at the Wagner in 1885, remain in their 1880s arrangement.<sup>12</sup> Only minor changes to the functional space of the building have been made to allow for its continued use as an educational institution.<sup>13</sup>

The current Wagner staff approach the maintenance and restoration of their building with a sensitive eye to conservation. Little has changed inside the building since the late 19th century. The result is a museum within a museum – the building itself and thus the exhibition hall ceiling are contributing components of this National Historic Landmark. In fact, the building itself is

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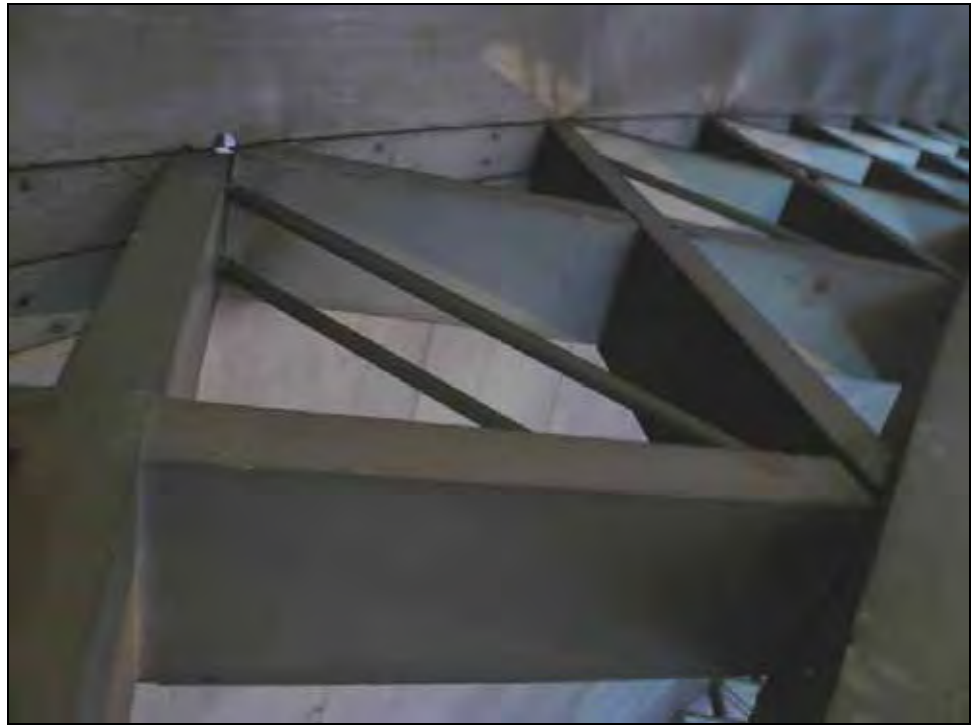
<sup>10</sup> Building Conservation Associates, Inc. “Wagner Free Institute of Science: Exhibit Hall Ceiling Conditions Assessment”. February, 2008, 24.

<sup>11</sup> Bolt, section 7, 2.

<sup>12</sup> Bolt, section 8, 5.

<sup>13</sup> Bolt, section 7, 4.

considered a part of the collection by the staff who aspire to the highest standard in preservation and conservation.<sup>14</sup>



**Figure 3: Arched truss in the Exhibit Hall. Photo by M. Goeke, 2008.**

The design for the Exhibit Hall is an ideal example of the utilitarian style of the rest of the building, “where the stacked iron columns and arched roof trusses are exposed to view, as in a Victorian train shed or London’s great Crystal Palace of 1851.”<sup>15</sup> The plaster ceiling is a vital component of the aesthetics of the gallery space and its retention should be carefully considered.

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<sup>14</sup> Susan Glassman, e-mail to author, 12 March 2008.

<sup>15</sup> Bolt, section 8, 3.

Conservation decisions at the Wagner cannot be taken lightly. Each and every piece of the original building contributes to the overall historic significance of the site, both interior and exterior. Moreover, changes to the building must be considered carefully as altering the building through the addition of new materials or systems can affect the performance of the existing fabric.



Figure 4: Exhibit Hall with temporary decking. Photo by M. Goeke, 2008

### *2.3 Exhibit Hall Ceiling Description*

The Exhibit Hall is the largest room in the building, spanning about 60 feet wide and 150 feet long, and rising two stories to the roof. The plaster ceiling is part of the larger system of the Wagner's roof. The barrel vault ceiling is divided into nine bays by eight arched trusses (Figure 4). The trusses are constructed of

two wood chords connected by steel ties and wood cross-bracing. Steel tie rods at the bottom of each truss provide reinforcement. The plaster spans the distance between the trusses and is not continuous through the whole length of the ceiling, resulting in nine separate bays of plaster, each approximately 60 feet wide by 16 feet long. Bays have been numbered for reference, with Bay 1 at the north end, and Bay 9 at the south end of the ceiling. The plaster continues from the ceiling onto to the walls which are similarly plastered. Thus, there is a continuous connection between the plaster ceiling and the north and south walls, and the east and west walls between the trusses.

Located within each of the even numbered bays is a skylight that spans the entire length of the bay, connecting to the trusses on either end, dividing the plaster into two separate fields on either side of the skylight. Along the length of the skylight, casement molding covers the edge of the skylight frame. This molding also appears to covers the edge of the plaster. Each skylight is approximately 100 sq. ft. in size and made of two wood sash divided into 32 panes. Placed in every other bay, the skylights once provided the exhibit hall most of its daytime light, but have since been covered over from above with plywood. Two hatches penetrate the ceilings in the north and south-most bays allow access to the roof.

## 3.0 GIS in Conservation

### 3.1 *What is GIS?*

A geographic information system, or GIS, is a system capable of integrating, storing, editing, analyzing sharing and displaying spatially referenced data. It is commonly used to understand geographical features and patterns to derive sensible spatial decisions.<sup>16</sup> It is broadly used in many areas including Urban Planning, cartography, logistics, etc. ESRI's software known as ArcGIS incorporates the methodology of a GIS into a computer-based software. ArcGIS requires a computer, reliable spatial data, and an informed operator who applies the capabilities of the software by posing interactive queries to thoroughly analyze all aspects of the problem to achieve an informed decision. The power of ArcGIS lies in its ability to process multiple and varying sets of data as well as store and display the information visually as a comprehensible and easily understood representation of data.<sup>17</sup>

ArcGIS can store spatial information in vector form - points, lines, and polygons - or in raster form as grid of continuous cells called pixels. Data associated with the spatial features are stored in attribute tables. Each form offers a different method of representation and analysis. Vector ArcGIS is useful for

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<sup>16</sup> Ian Heywood, Sarah Cornelius and Steve Carver, *An Introduction to Geographical Information* (Edinburgh Gate: Pearson Education Limited Systems, 2006), 18.

<sup>17</sup> *ArcGIS 9: What is ArcGIS 9.2?* (Redlands: ESRI, 2001), 4.

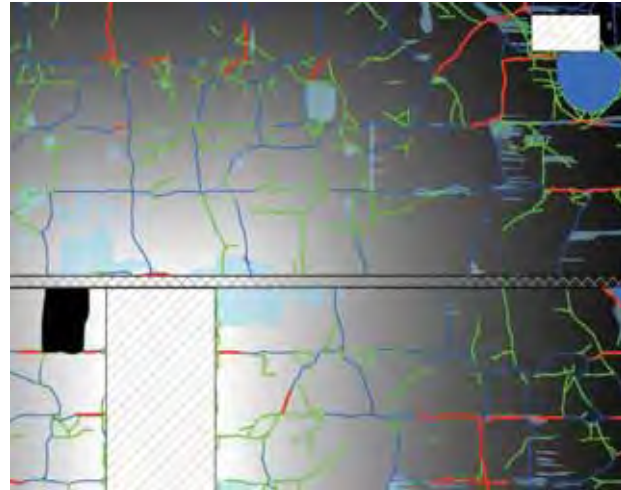


objects with distinct shapes, such as roads or states. Raster ArcGIS records data as a grid of cells which contain numerical values relating to the attributes of that cell. Raster GIS better represents objects or conditions where edges are not clearly defined, like elevation maps, or proximity to locations.

While ArcGIS is an excellent tool for the graphic display, analysis and interpretation of data, its drawing capabilities are somewhat limited. Another type of software, Autodesk's AutoCAD, is ideal for the initial documentation process. It allows the user to assign common elements to independent layers, allowing for individual layers to contain all instances of a single element. The AutoCAD drawing is then imported into the ArcGIS. The AutoCAD files are converted within ArcGIS where the individual layers can be separated into their own ArcGIS shapefiles. Shapefiles can then be symbolized with colors and patterns to create a visual representation of the existing conditions. Conditions are generally recorded into vector files, such as lines for cracks and polygons for areas of loss. ArcGIS software provides a wide range of extensions such as clipping and buffering tools to isolate and manipulate areas of specific interest.

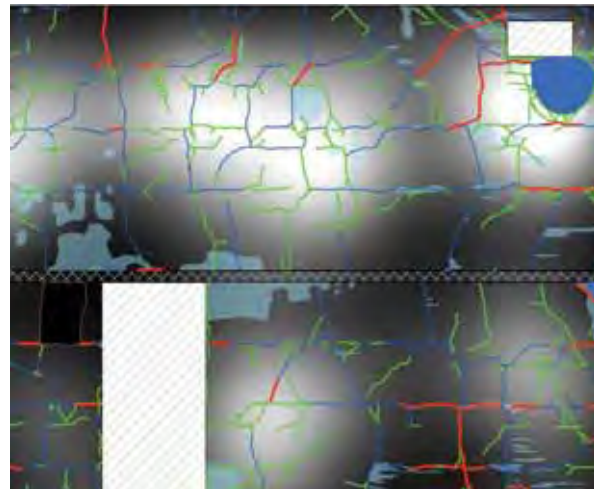
ESRI's ArcGIS 9.2 was selected for use in this analysis. Another particularly useful piece of software is Spatial Analyst. Spatial Analyst is an extension of ESRI's ArcGIS and is the tool used to convert vector data to raster data. It provides unique analysis methods for use with raster-based files to create new

information to identify and represent spatial relationships.<sup>18</sup> A simple example of the use of Spatial Analyst is with urban planning. Spatial Analyst can aid in the decision of where to locate a particular venue, such as a school, by compiling different data sets of relevant information, like elevation, zoning, distance to other schools, and distance to existing roads, to create new raster data.



**Figure 5: Distance from skylight. Black and white raster is overlaid with vector conditions in color.**

The new data is then combined with the other parameters to illustrate the most suitable areas for the given venue.



**Figure 6: Density of small cracks with vector overlay.**

Spatial Analyst may also be a valuable tool in the context of building conservation. A building is more than a sum of its visible conditions and Spatial

Analyst allows for analysis of factors that may influence the overall conditions,

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<sup>18</sup> Jill McCoy and Kevin Johnston. *Using ArcGIS Spatial Analyst*. (Redlands: ESRI, 2001), 3.

such as proximity to a structural element or the density of a particular condition. It offers several analysis tools to create raster maps that may prove useful in this application. The most common rasters used in this methodology are based on “distance-” and “density” analysis. Distance analysis creates a raster with grid values from a selected file, vector or raster, which represents the values of the distance from the feature. For example, distance analysis could be run on the skylight polygon feature to determine the locations that are farthest from those features. Density analysis can be created only from point and line files (no polygons). It is useful for identifying areas of concentration of an attribute that may be visually unclear in a vector file. It is particularly useful for representing cracks. Maps created through the use of ArcGIS combined with the results from Spatial Analyst can then be used to explore relationships among conditions.

### ***3.2 GIS Applied to Historic Preservation***

GIS is becoming more common in the cultural resource field as it provides preservationists with a software tool that can link spatial information with documentary and archival information, allowing for a better visual presentation of information as well as analysis of the data. Cultural resource managers can use GIS to create an organized way of storing and sharing data gathered about resources over large geographic areas to ensure adequate and continued maintenance. In addition, they can use GIS to identify areas that may be at risk of

natural disasters or development, or to enhance their understanding of the historic significance of a site.

For example, GIS can aid in the management and understanding of historic districts by offering cultural resource managers a way to illustrate how geographic areas change over time. As an illustration, in 1996, Port Penn, a National Register Historic District in Delaware, developed a GIS that used historic maps to monitor the town's growth starting from 1792. It mapped building-specific attributes as well as archived floor plans and photographs of each building. It enabled attributes, such as construction data, architectural style, and use to be visualized on maps which illustrate the geographic relationship between the various attributes, thereby revealing otherwise hidden trends in the evolution of the town.<sup>19</sup>

In *Past Time, Past Place*, editor Anne Knowles advocated for the use of GIS as a way to enhance our understanding of history. She stated that:

The ability of GIS to integrate, analyze and visually represent spatially referenced information is inspiring historians to combine sources in new ways, to make geographical context an explicit part of their analysis, to reexamine familiar evidence, and to challenge long-standing historical interpretations.<sup>20</sup>

A similar argument can be made for building conservation. While geography may not be of interest to the conservator *per se*, spatial relationships between observed conditions and building materials is an essential component of

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<sup>19</sup> Deidre McCarthy. "Applying GIS Technologies to CRM." *CRM* 21, no. 5 (1998).

diagnosis. While most GIS is geo-located, ArcGIS can be used to map data points in relation to each other independent of the globe. GIS can be a valuable tool for conservators as it provides a way to illustrate and correlate multiple conditions and other information about a building into one spatial representation. Moreover, the quantitative analysis possible with GIS can result in a richer understanding of building pathologies. As an example, it can be used to calculate the extent of a condition like surface loss. Identifying correlations and exploring relationships between attributes like conditions can more precisely determine areas of concern and highlight the extent to which they pose problems.

GIS, however, is just coming into use as a tool for building conservation. To realize its full potential will require experimentation and exploration. An early use of GIS for conservation was the documentation and assessment of stone at the Jefferson and Lincoln Memorials, in 1998. GIS provided a way to link condition information with particular stones, allowing for better interpretation of conditions that lead to improved monitoring and maintenance of the sites.<sup>21</sup> The use of GIS was also cited in a study on the conservation of wall paintings in GraDOC from 2000. Gaetano Palumbo discussed the potential of the combined use of CAD and GIS to help conservators make more informed intervention

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<sup>20</sup> Anne Kelly Knowles, ed. *Past Time, Past Place: GIS for History*. (Redlands: ESRI Press, 2002), xiii.

<sup>21</sup> Kyle Joly, Tony Donald and Douglas Comer. "Cultural Resources Applications for a Stone Conservation at Jefferson and Lincoln Memorials." *CRM 2* (1998): 17-18.

decisions.<sup>22</sup> Research into additional applications for the software is continuing and should prove to be a valuable methodology for future generations of conservators.

### ***3.3 ACL's GIS Assessment at Drayton Hall***

In 2001, the Architectural Conservation Laboratory (ACL) at the University of Pennsylvania embarked on a project at Drayton Hall in South Carolina. This project sought to explore the conditions of a cracked decorative plaster ceiling to determine the best course of treatment. A description of the project was published in the *APT Bulletin* in 2003.<sup>23</sup> Using traditional methods, current conditions of the ceiling were recorded and documented to inform later treatment decisions. During this project, the ACL devised an innovative method of analysis of the crack patterns using GIS. Working with ESRI's ArcView 3.2 and the Spatial Analyst extension, researchers were able to explore the spatial relationships between conditions on the plaster and the supporting structure. The team also developed statistical correlations among the conditions using regression analysis. The results of the analysis produced clear and informative maps that provided numerical data on the extent of the area requiring treatment.

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<sup>22</sup> Gaetano Palumbo. "Beyond CAD: a look at data integration and analysis using GIS," in *GraDoc: graphic documentation systems in mural painting conservation: research seminar, Rome 16-20 November 1999*, edited by Werner Schmid. (Rome: International Centre for the Study of the Preservation and the Restoration of Cultural Property, 2000), 114.

<sup>23</sup> 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): 25-35.

Having created a detailed “threat map,” conservators isolated areas that required treatment and minimized the potential for overtreatment of the ceiling and possibly causing further damage or spending limited funds on unnecessary treatments.

The research at Drayton Hall proved to be useful for that particular ceiling as it provided the conservators with a visual map illustrating the areas of potential threat. Treatment was pursued and proved to be successful on the areas identified through the GIS analysis. However, the methodology used in the Drayton Hall project has not been applied to other ceilings to test its general efficacy as an analysis tool of broad approach. Furthermore, the GIS analyses were never fully evaluated nor supported with alternative methods of investigation. Instead, the result of only one regression model was tested, not enough to identify it as a broadly applicable modeling tool.

Evaluating the GIS methodology on the plaster Exhibit Hall ceiling at the Wagner is a logical, next step and non-destructive testing using the results of the analysis could help confirm the efficacy of GIS modeling. The Wagner Institute and Drayton Hall both exhibit a cracking pattern that is widespread throughout the ceiling. However, the ceilings do differ in some specific, defining characteristics. One major difference is that the ceiling in the Wagner Institute is a barrel vault, whereas the Drayton Hall ceiling is flat. Thus, the Wagner ceiling may act differently from Drayton Hall since it functions as an arch. Furthermore, the Wagner’s ceiling is connected directly to the roof of the building and not to

an additional floor, like Drayton Hall. Thus, the Wagner ceiling experiences different movement and loading patterns which can contribute to the cracking of plaster. Also, the Drayton Hall ceiling is constructed in a single continuous section, whereas the Wagner ceiling is divided into nine sections separated by the wood trusses. Further, the materials of the two ceilings may be vastly different, particularly if the builders relied on locally produced materials. The type and quality of construction materials can have a significant impact on the behavior of a building.

There are also some limiting factors in analyzing the Wagner ceiling. One, researchers at Drayton Hall were able to compare the conditions assessment and subsequent analysis with a previous assessment of the ceiling. This allowed for a more comprehensive understanding of perceived areas of detachment and of how the cracks may be forming. Two, building movement of the Wagner is unknown. Monitoring of the building and cracks is scheduled to begin in the summer of 2008. Until the results of the monitoring are evaluated, an explanation for the cracking can only be an educated guess. However, a comprehensive GIS analysis can be used to help interpret the results of that data once it is available.



## 4.0 Methodology

### 4.1 *Diagnostic Process*

Conditions diagnosis is an on-going process, requiring repeated review as new information becomes available through continued observation and monitoring. Hypotheses will likely be revised and fine-tuned to reflect the current knowledge. Each step in the process is vital to gaining a comprehensive understanding of the causative factors of a condition and how they might be mitigated. A conditions assessment is the first step towards understanding the deterioration mechanisms acting on a building.

A visual examination of the Wagner's ceiling is one of many factors used to determine its condition and its vulnerability to damage. Many factors can cause damage and these should be thoroughly assessed and combined with the visual conditions to enable a full picture of the total condition of the structure. These factors include but may not be limited to: material installation and composition; the design and construction of the building; the building's environment, including interior and exterior factors; and past treatments and maintenance. All of these factors need to be examined to determine the likely causes of deterioration to the ceiling to inform the overall analysis and enhance the interpretation of the results. While a GIS can be useful for analysis, conditions diagnosis of unseen conditions is only as good as the investigator and the tools

they employ in the investigation. A GIS is a tool which can significantly contribute to the overall set of tools used, providing new data for interpretation and leading to more sound hypotheses.



Figure 7: Bay 4, facing west. Photo by M. Goeke, 2008.

#### **4.1.1 Conditions Assessment**

The first step in the diagnostic process is a conditions assessment, which will provide the physical documentation on which the GIS analysis can be run. Conditions surveys should not only display existing conditions, but also the spatial relationships among the conditions, recorded on spatially-rectified photographs.

As a result of concerns about the stability of the plaster, a conditions assessment of four bays was performed in 2007 by the University of Pennsylvania and Building Conservation Associates, Inc. and the results compiled in a preliminary report.<sup>24</sup> Documentation from this assessment serves as the basis for the GIS analysis in this thesis. An additional bay was assessed in January of 2008 and added to the existing documentation.

Although conditions assessments are vital to understanding deterioration processes, they should not be used in isolation. In “Monitoring, Interpretation, and Use of Data,” a technical note published by the J. Paul Getty Trust, author Michael Henry points out the limitations of the conditions assessment.

When we observe present conditions, we are making a “single point” observation of the process. This single point observation does not inform our understanding of the rate of change, deterioration or decay, especially with slow processes over time.<sup>25</sup>

This is particularly important to note at the Wagner, where the crack pattern has been visible for at least 20 years and it is unknown if there has been any changes to the pattern during that time period. Little understanding of how the cracks formed can be gained through a single point observation alone, and should be supplemented by additional research, repeated observations, and monitoring.

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<sup>24</sup> Building Conservation Associates, Inc. “Wagner Free Institute of Science: Exhibit Hall Ceiling Conditions Assessment.” February, 2008.

<sup>25</sup> Michael Henry. “Technical Note: Monitoring, Interpretation and Use of Data.” (Los Angeles: J. Paul Getty Trust, 2003.)

A preliminary report by Donald Friedman of Old Structures, Inc. on the load-bearing capacity of the roof trusses was completed in 2005 and will be reviewed to understand the potential impact of expected building movement.<sup>26</sup>



Figure 8: Probe 1. Photo by A. Finke, 2007.

#### 4.1.2 Physical Investigation

Roof probes from June of 2007 also contributed to the overall understanding of the plaster ceiling. Six probes, each approximately 1 sq. ft. in area, provided visual evidence of unseen conditions and were related to the visible conditions below.

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<sup>26</sup> Donald Friedman. Letter to W. Stivale, 19 September 2005.

### 4.1.3 Materials Research

Understanding the characteristics of the construction materials is vital to determining the causes for deterioration. Laboratory analysis and field observation of the plaster system will inform the assessment of the ceiling from a materials standpoint. Petrographic and chemical analysis of the plaster was performed by Testwell Laboratories in 2007 and is included in BCA's preliminary report on the ceiling. Relevant findings from that study are reviewed along with research on the history of plaster technology. Together, this information contributes to our understanding of the expected and observed performance of the ceiling.



Figure 9: Large crack. Photo by M. Goeke, 2008.

#### **4.1.4 Archival Research**

Archival research provides a basis for understanding why a building may be performing as it is. Research should include factors relating to the building's specific history, including alterations, significant events, past conservation treatments and on-going maintenance. Past conservation treatments as well as long-term maintenance of the building and its materials can have a great impact on the ability of the materials to function today. Documented repairs should be examined to note the existence of continuing problems and determine if the repairs could alter the way the building functions. Maintenance, or lack thereof, impacts the longevity of materials and systems and should be another aspect of the total assessment. The building archives at the Wagner Free Institute were visited to examine documentation of building changes or other events that may affect the plaster ceiling.

#### **4.1.5 Building Context and Environment**

Building context, including location, climate, transportation, neighboring buildings, are other areas of interest. The context of the building can contribute to things like movement of the structure. Fluctuations in temperature and relative humidity can cause building elements to expand and contract. If allowed to infiltrate the building, water from precipitation can have a significant impact on building elements like plaster, wood and nails by weakening the materials through dissolution and corrosion. Exterior factors around the building itself can

contribute to the building's ability to exist in a healthy environment. Trees and other tall buildings can block solar radiation, causing areas that are wet to remain wet for longer periods of time, or impact the foundation causing movement of structural elements. Changes in vehicular traffic patterns can contribute to increased vibrations acting on the building. Weather data collected for the site is presented, along with a brief examination of external factors that may contribute to the performance of the building.

#### **4.1.6 GIS Analysis**

Information from the traditional assessment noted above will provide a basis for a working theory as to what caused the problem and how to deal with it. These findings can be substantiated with data from the GIS analysis. Additionally, GIS can utilize the data gathered from the conditions assessment to compose a visual model of the ceiling with extensive capabilities for exploring interactions among the variables.

#### **4.1.7 Nondestructive Testing**

Additional nondestructive methods to confirm the results from the GIS were researched. Known methodology is limited for wood-based plaster systems, and none appeared to enable validating the GIS findings. Scanning Laser Vibrometry was tested on mock-ups of the plaster ceiling but was deemed inconclusive.<sup>27</sup>

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<sup>27</sup> Jesse Zoll, Steve Young and Dean Capone. "The Use of Scanning Laser Dopple Vibrometry for Non-destructive evaluation of Structural Flaws in Plaster." (Applied Research Laboratory, The

However, testing continues on the efficacy of this nondestructive technique for the Wagner ceiling problem.

Together, the information gathered from these investigations and tools will provide a more substantial understanding of the conditions of the Wagner Institute's ceiling. The synthesis of the gathered information will ultimately result in a stronger hypothesis about the nature of the damage to the plaster ceiling.



## 5.0 Exhibit Hall Ceiling Assessment

### 5.1 *Conditions Assessment*

#### 5.1.1 Conditions Documentation and Observation

Two University of Pennsylvania graduate students (M. Goeke, A. Finke) assessed four bays of the ceiling in the summer of 2007 and an additional bay was assessed in January of 2008 by one of the students (M. Goeke). The five bays include one end bay, two bays with skylights and two bays without skylights. The data used from these five bays were determined to be representative of the regular patterns on the ceiling and each type of bay. To record the existing conditions of the Wagner Exhibit Hall ceiling, they created a base map for use during the survey. The base map consists of a non-reflected, rectified photomontage of the plane of the ceiling onto which conditions can be documented. The end result is a flattened representation of the curved surface.

Before beginning the assessment, relevant conditions were identified and color coded to represent the conditions on the field drawings. These conditions were then mapped on the photomontage. The conditions noted were:

- Small, medium and large cracks
- Displacement
- Total loss
- Partial loss
- Areas of previous repair
- Water staining
- Surface accretion

Areas of perceived detachment of the plaster from the lath was also noted, but not used as a condition in the analysis. Detachment is generally determined by lightly tapping the surface while listening for a hollow sound. It was not used as a condition because it can be misleading and difficult to identify, particularly when assessments are performed by multiple people who may hear things differently.

Observations were recorded in the field on the rectified photomontages of each bay. Using AutoCAD, those conditions were traced over the rectified photomontage to create a digital full scale drawing of the conditions. Each condition was recorded on a separate layer. This allows for isolation of conditions. Ceiling framing, as it was understood through limited roof probes, was also recorded in the CAD drawing. These drawings were brought into ArcGIS and served as the basis for the GIS analysis.

Extensive cracking was observed in all bays throughout the ceiling. Most cracks appear to run north/south and east/west, with some diagonal cracks observed. The cracks follow a general rectangular pattern throughout the ceiling, despite the fact that the plaster in each bay is essentially independent from the others. Three sizes of cracks were documented: small (less than 0.25 mm wide); medium (0.25 mm but less than 1 mm wide) and large (1 mm wide, and larger). (Appendix A, Map 1)

Plaster displacement is defined as out-of-plane movement of the plaster and occurs with cracking. It can be used as an indicator of detachment. For areas not bordering wood members, displacement can only be measured against the plane of the plaster adjacent to it and thus does not represent the true measure of the plaster's detachment from the lath. If both planes have displaced the same amount, displacement may not even be visible. Plaster displacement along the truss was measured from the bottom edge of the dimensional lumber attached to the bottom of the upper wood chord (screed). In this area, movement of the plaster can result from three different types of movement: movement of the entire nailer/lath/plaster assembly in relation to the truss; movement of the plaster with the truss but not the nailers or the lath; or movement of the plaster independent of the lath, nailers, and the truss. Only the last implies detachment. It is impossible to know which kind of movement is occurring when observing only the underside of the ceiling. In all cases, considerable movement of the plaster is deemed to be a problem as continued movement of all kinds weakens the surface.

Displacement is of great concern as it indicates a potential for plaster detachment. Displacement was measured along cracks and divided into 7 size ranges: (Appendix A: Map 2)

- less than 1 mm
- 1 to less than 2 mm
- 2 to less than 3 mm
- 3 to less than 5 mm

- 5 to less than 10 mm
- 10 to less than 20 mm
- equal to or greater than 20 mm

As expected, the cracking was the most extensive condition recorded. Water staining was observed in several areas, but did not appear to be a widespread condition. However, due to the detrimental effects that water has on plaster, it is a serious concern. Displacement may also be a serious concern, but large displacement (>5 mm) was somewhat limited to areas along the trusses. Widespread small-sized displacement did occur, and may be a result of lost adhesion between the plaster and the lath.

There were a number of very small areas of partial loss, which is loss of the surface layers of plaster from the scratch coat. These areas tended to be no more than a few inches in diameter, and often appear along a crack or in the corner of a bay. Partial loss along cracks could be a sign of movement of the crack, a result of the edges of the crack grinding against each other.

Several sections of previous repair were found. Most resulted from probes conducted around the truss ends along the wall edge of the plaster. In addition, one large area by the roof hatch was also repaired. The staff indicated that the repair was made prior to the early 1990s, and are unaware of the nature and extent of the damage.

There are only two areas of total loss that have not previously been repaired (i.e. total loss): the piece that fell in 2003 in Bay 2, and a very small piece near a

truss end in Bay 3. The loss from 2003 was retained for analysis, but the condition of the piece when it fell was not documented. It would have been valuable to observe the edges of both the plaster piece and the gap just after the loss. The condition of the edges might have given some insight into the type of cracking and an understanding of why the piece fell.

### **5.1.2 Roof Probes**

Six probes were conducted on selected openings made on the roof to examine general conditions on the opposite side of the plaster ceiling, including the conditions of the plaster keys. (Appendix A, Map 2) Keys are the mechanical method through which the plaster is attached to the ceiling and are of paramount importance to the integrity of the plaster. Damaged keys represent the greatest threat to the ceiling. Keys can be damaged in a number of ways. Keys that have broken along the length of the lath no longer have the mechanical attachment to the underside of the plaster and can result in detachment of the plaster from the lath. Keys can also break perpendicular to lath. Though limited in scope, the roof probes allowed for the examination of the keys around areas of visible damage below to try to correlate conditions.

The probe locations were chosen to evaluate different conditions visible on the ceiling that were of interest: the area above the total loss; an area of severe displacement and water staining near a truss and a skylight; an area of significant water staining and cracking; an area with small and medium cracks;

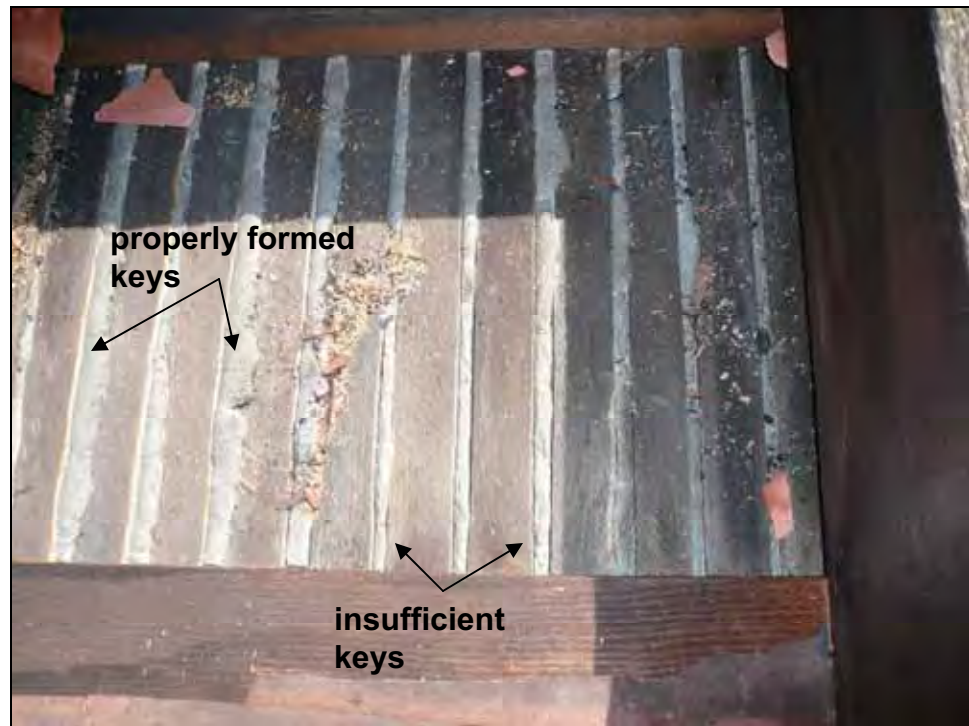
an area of perceived detachment and diagonal cracking; and, for comparison, an area of small cracks which appeared to be in good condition from below.



**Figure 10: Probe 2, above area of water staining and displacement. Note the layers of roofing material and the water damage to the roof paper. Photo by M. Goeke, 2007.**

The probes were valuable for several reasons. One, they offered a clearer understanding of the interior structure of the ceiling and roof. Two, they revealed conditions that cannot be seen from below but may be significant, such as insufficient- or broken keys. Insufficient keys are ones that were not properly formed, so they lack the mechanical attachment to the lath. The probes revealed that some of these have actually dropped, resulting in detachment. Three, the

probes directly linked the visible water staining below with poor conditions of the lath, keys, and framing elements. Water staining was visible in two of the



**Figure 11: Probe 6. Insufficient keys, where the plaster does not slump over the lath, do not have the proper mechanical attachment to the lath. Photo by M. Goeke, 2007.**

probe locations, which proved to be the two areas in the worst condition when viewed from above. Because of this, the location of water staining will be a significant factor for the GIS analysis. Four, the area perceived to be in good condition from below appeared sound and intact above, indicating that the visible conditions below can be a useful guide to the overall condition of the ceiling. (Appendix A: Map 3)

## 5.2 Materials Research

### *Plaster History and Technology*

Plaster can be both a substantial and decorative finish. It has been used for centuries to finish buildings, and can be painted, decorated, or textured, and made to imitate other building materials. Plaster technology in the late 19th century is well documented in contemporary building trade books. Reviews of these texts provide a thorough understanding of how the ceiling works, and how the system should perform over the long term.

The publication of Nicholson's *Mechanical Exercises* in 1812 is one of the earliest texts about the building trades.<sup>28</sup> Nicholson subsequently published many books that include detailed discussions on plastering during the 19th century. Publications from the mid-19th century become more in depth as they divide the building crafts into specialties. Shaw's *Practical Masonry* (1846) exclusively discusses the use of masonry as a building trade and includes a substantial section on plastering.<sup>29</sup> Robson's *The Mason's, Bricklayer's, Plasterer's and Decorator's Practical Guide* (1859)<sup>30</sup> and Burn's *Masonry, Bricklayer and Plastering* (1871)<sup>31</sup> added significantly to the developing plaster trade.

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<sup>28</sup> Peter Nicholson, *Mechanical exercises; or, The elements and practice of carpentry, joinery, bricklaying, masonry, slating, plastering, painting, smithing, and turning...*(London: J. Taylor, 1812).

<sup>29</sup> Edward Shaw, *Practical masonry, or, A theoretical and operative treatise of building...*(Boston: B.B. Mussey, 1846).

<sup>30</sup> Robert Robson. *The mason's, bricklayer's, plasterer's, and decorator's practical guide...*( London: James Hagger, 1859-62.)

<sup>31</sup> Robert Scott Burn. *Masonry, bricklaying and plastering.* (1871. Reprint, Shaftesbury: Donhead, 2001.)



By the late 19th century, large encyclopedias on the plastering craft were also published. Millar's *Plastering Plain and Decorative* (1897)<sup>32</sup> and Verrall's *The Modern Plasterer* (1927)<sup>33</sup> are two important books that provide an extensive review of historic and contemporary knowledge about plaster. A review of these texts provides a good understanding of plastering tradition as it applies to ceilings and how the finished system should perform over the long term. The plasterers who worked on the Wagner were likely aware of the teachings in these texts.

Generally, plaster is a mixture of lime, aggregate and water, much like a traditional mortar. Depending on use, gypsum (referred to as plaster or plaster of Paris in historic literature) can be added, which provides a smooth finish and a quick set that does not shrink upon drying. For historic building plaster, gypsum is generally added only to the finish coat. Additives, like hair and sand, can also be included to enhance the curing process, or to provide additional strength or color.

Lime and gypsum are binders for plaster. Lime is formed by burning limestone (a sedimentary rock) at high temperatures, which reduces the major component, calcium carbonate, into calcium oxide or "quicklime". The

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<sup>32</sup> William Millar. *Plastering, Plain and Decorative*. (1897. Reprint, Dorset: Donhead, 1998.)

<sup>33</sup> W. Verrall. *The Modern Plasterer*. (1927. Reprint, Dorset: Donhead, 2000.)

quicklime is slaked with water and converted to calcium hydroxide. This product is called “slaked lime” or lime putty and is the starting material for lime-based mortars and plasters. Slaked lime is mixed with water and is converted to calcium carbonate through a reaction with atmospheric carbon dioxide. The water evaporates, and the calcium carbonate that forms acts as a binder that holds together the mortars and plasters made from lime. Lime-based mortars take a long time to set and shrink upon drying which can cause small cracks in the plaster. Gypsum is often used with lime to take advantage of its quick set and slight expansion upon drying. In plastering, it is often used as the only binder in the finish coat as it provides a smooth surface without cracks.

An aggregate, usually sand, is added to the mortar mixture to provide strength and minimize shrinkage. The aggregate serves to bulk up the mix so that there is less lime to shrink and makes the plaster easy to apply. Aggregate particles fill out the mixture, and the interactions between them serve to lock the mixture in place when dry. The grading and quality of the aggregate will impact the final performance of the mortar. Since plaster requires good tensile properties as it is laid vertically on walls or horizontally on ceilings, additives like hair are often included in the mix.

Water is another vital component in plaster. Historic texts don't note the amount of water used in a mix, since it will vary depending on the specific mortar and environmental conditions. Water renders the plaster fluid, which is

required for forming adequate keys and creating a smooth surface. It also initiates the chemical reaction that allows the material to set or cure. Too much water will make the plaster too fluid, and the keys formed will be weak. Moreover, the water in lime-based mixes must evaporate to cure into the finished plaster. Excess water will slow curing and result in more cracking in the finished plaster.

Recipes for mortar have remained essentially constant over time. Most early trade books starting in the 18th century quote Vitruvius' formula of one part lime to three parts sand.<sup>34</sup> This basic volumetric ratio is commonly used for exterior masonry mortar as well as in the scratch coats of plaster. A 1927 text by A.D. Cowper does point out that ceiling work can sometimes be executed with a lower sand/binder ratio – 2 or 2.5 to 1.<sup>35</sup>

Most early texts divide plaster mixes into two types, classified by the following terms: “coarse stuff” and “fine stuff.” Coarse stuff is essentially lime, hair, sand and water, and can be gauged with plaster as needed. Fine stuff can be either slaked lime alone or mixed with a bit of sand, hair and/or plaster, depending on the author. Fine stuff can be used as a finish coat or can be mixed to be used in pulled plaster. As the plaster gets closer to the finished surface, less

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<sup>34</sup> Vitruvius. *The Ten Books on Architecture*. Translated by Morris Hicky Morgan. (Reprint, Cambridge: Harvard University Press, 1914), 43.

<sup>35</sup> A. Cowper. *Limes and Lime Mortars*. (1927. Reprint, Dorset: Donhead, 1998), 43.

sand is used. Finish plaster consists of very little sand to provide a smooth surface for paint or wallpaper.

The ceiling of the Exhibit Hall is finished in flat plaster, contributing to the utilitarian aesthetic of the room. Flat systems can be installed either on wood and lath framing, as on the ceiling, or directly on masonry, as on the brick walls. Usually, flat plaster is applied in three layers. The first layer is commonly called the scratch coat, although in historic literature it is often referred to as the “pricking up coat.” The scratch coat, made of coarse stuff, creates the keys in lath framing systems, and is formulated to receive and bond well with subsequent layers. The scratch coat is scratched to create a key for the next layer, referred to as a floating coat or brown coat. A brown coat is achieved through the use of a screed, which allows the plasterer to even out the coat to a straight line. The third and final layer, the setting or finish coat, is thinner and usually consists of simple lime putty, to which a plasterer may add a gauge of plaster of Paris to make it set faster. This three-coat method is found on the ceiling at the Wagner.

#### *Exhibit Hall Ceiling Plaster*

Portions of the fallen plaster were used for a detailed plaster analysis by Testwell Laboratories as part of BCA’s Preliminary Assessment. The plaster analysis provides a characterization of the plaster mix, which determines the performance and durability of the plaster. In general, the analysis showed that

the plaster was well mixed, provided good bonding in between layers and did not show a predisposition toward cracking as is visible in the ceiling today.<sup>36</sup>

Testwell identified the three coats in the Wagner sample, consistent with historic literature. The plaster appeared well-compacted to the lath and no wood fragments were found in the plaster, indicating that it may have already released from the lath before falling from the ceiling.<sup>37</sup> Analytical results for the brown and finish coats appear typical when compared with the historic literature. The scratch coat was atypical.

The plaster averaged 9/16 inch thick and the scratch coat ranged from 1/8-3/16 inches thick. *In Plastering, Plain and Decorative*, Millar made the following recommendations regarding the thickness of a plaster scratch coat:

The thickness should not exceed 5/8 inch, or be less than 3/8 inch. If too thick, it tends to weigh down the lath work and is apt to crack; if too thin, the subsequent scratching is liable to cut the coat down nearly to the laths, thus leaving a series of small detached parts which are unstable, form a weak foundation for the floating coat and are a source of cracks, and often the cause of the work falling when subjected to vibration. A thickness of 1/2 inch gives best results.<sup>38</sup>

The fact that the scratch coat in the Wagner sample is thinner than recommended could be a significant factor when considering the crack pattern.

The scratch coat also comprised unusually low sand to binder ratio (1.3:1) and a lower amount of hair than usually found in historic plasterwork. Both of

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<sup>36</sup> Testwell, Inc. Historic Masonry Evaluations, Wagner Free Institute of Science. 17 November 2007.

<sup>37</sup> Testwell Inc., 10.

these issues can compromise the integrity of the finished plaster. This sand/binder ratio is below Cowper's recommendation for ceilings, which could cause performance problems.<sup>39</sup> Sand is added to the scratch coat to mitigate shrinkage and a deficiency could result in minor shrinking and cracking and cause the plaster to pull away from the lath. This could be the cause of gaps in between the lath and the plaster as viewed in the roof probes. However, Testwell did not report extensive shrinkage that would point to larger problems.<sup>40</sup>

Chemical analysis of the ceiling sample revealed significant levels of magnesium, indicating that it came from a dolomitic lime source, commonly found in the Philadelphia area. It is often called "meager lime" because it takes a long time to slake and produces less binder once slaked. Because it slakes slowly, sometimes slaking can continue after it forms the plaster. Cowper describes the consequence of slaking lime in a plaster as pitting of the surface due to the expansion of the lime in the matrix.<sup>41</sup> Pitting of the lime was not observed in the plaster sample from the Wagner, nor is it visible on the surface of the ceiling.

There is some uncertainty over the characteristics imparted by high magnesium content in lime, and its characteristics are not addressed in all historic texts. While Vicat notes that hydraulic limes must include silica, the

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<sup>38</sup> Millar, 91.

<sup>39</sup> Cowper, 43.

<sup>40</sup> Testwell Inc., 11.

translator of this text adds that magnesia can offer the benefits of hydraulicity without silica and can set underwater.<sup>42</sup> Cowper notes that dolomitic limes ultimately develop greater strength than high-calcium limes.<sup>43</sup> Eckel notes that, although they take longer to slake, they perform better in long-term tests than high calcium limes.<sup>44</sup> Tensile strength testing published by Eckel also verify the long-term high strength of magnesian limes.<sup>45</sup> Thus, it appears that limes with a high content of magnesium may be stronger than high-calcium lime. High strength imparted by the dolomitic lime may help explain the 120 year performance of the Wagner ceiling despite clear problems with cracking and water infiltration.

### *5.3 Design and Structure*

#### **5.3.1 Description of Structural Elements**

The design and subsequent construction of a building has a great impact on its longevity. Quality craftsmanship, attention to detail, and appropriate use of materials can greatly extend the service life of a building. The framing of the ceiling and roof are one of the leading variables in the longevity of the ceiling.

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<sup>41</sup> Cowper, 30.

<sup>42</sup> Vicat, 34.

<sup>43</sup> Cowper, 52.

<sup>44</sup> Edwin C. Eckel, *Cements, Limes, and Plasters: Their Materials, Manufacture and Properties*. (New York: John Wiley and Sons, 1928), 117.

<sup>45</sup> Eckel, 125.

Verrall, in his 1927 book *The Modern Plasterer*, makes specific reference to the importance of the design of a ceiling for the stability of subsequent plaster work:

The state of the base upon which plaster is applied is perhaps the most important item in the obtaining of satisfactorily completed plastering. This is particularly so in the case of lathing and lath-and-plaster work, and of this type especially ceilings, due to the fact that they are generally of comparatively large area and that the weight is suspended in a horizontal position, that this part of the work is usually not covered with any material which will tend to conceal cracks or other defects that might occur, and that the appearance of the ceiling, attracting the eye as it does, will have a large part to play in making or marring the complete finish of the room.<sup>46</sup>

The ceiling and roof at the Wagner share the same structural system. As there are no historic drawings of the building's design, information was gathered mostly from physical investigation. Roof probes and archival research provided information about how the system is constructed, and the results of measurements taken from the probes were extrapolated to encompass the entire ceiling.

The roof and ceiling are supported on eight trusses, running east/west dividing the plaster ceiling into nine bays. Wood purlins provide a surface for attaching both the interior and exterior framing and run on top of the trusses. The wood deck is comprised of tongue and groove boards and is fastened to the top of the purlins, adding structural stability to the entire system by providing rigidity to the entire framing system and spreading any live loads. Nailers

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<sup>46</sup> Verrall, 96.



fastened to the underside of the purlins provide space onto which the lath are nailed. The three-coat plaster work is applied to the wood lath.

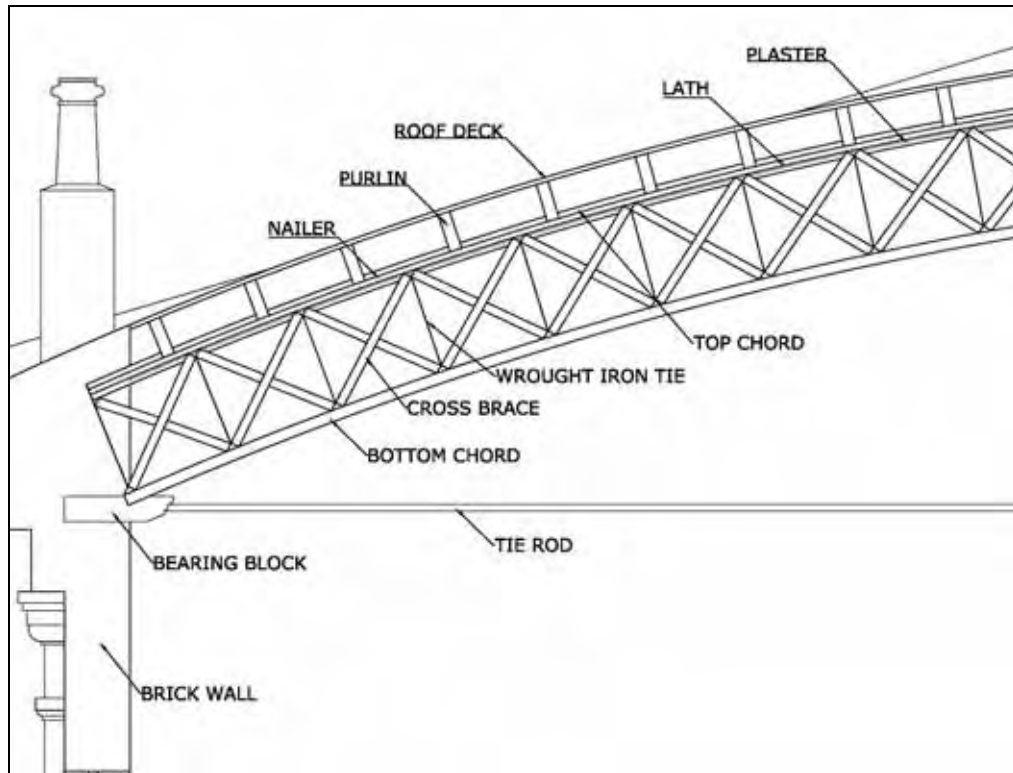


Figure 12: Detail of ceiling structure. Drawing by M. Goeke based on drawings by Mark B. Thompson, Associates.

### *Trusses*

The trusses are said to be designed from a patented system; details of that patent could not be located.<sup>47</sup> Carl Condit makes reference to a similar vaulted roof design constructed of wood for the Philadelphia, Wilmington and Baltimore Railroad Station (1851-1852), the first of three Broad Street Stations in

Philadelphia. The trusses there spanned 150 feet between brick side walls with a wrought iron tie-rod and iron hanger support.<sup>48</sup> The design sounds very similar to the contemporary design at the Wagner, only on a larger scale.

The wood trusses are constructed of two chords that are connected by steel ties that bind the two chords together. Wood cross-braces sit in between the ties approximately 22 inches apart. Because of their length, each truss chord is constructed of multiple pieces of wood. The lower chord is approximately 7  $\frac{3}{4}$  inches wide and 2  $\frac{1}{2}$  inches high and constructed of two pieces. The intersection of the two pieces of the lower chord is visible in each truss, and the placement alternates between being approximately 18 feet from the east, as in truss one, to 18 feet from the west in truss two. The spliced ends are cut at an angle and attached with three large bolts. The top chord is invisible from the underside, but in the area of plaster loss, it is clear that the upper chord is similar to the bottom chord, and that it also is formed in two pieces that are spliced together with steel bolts.

Two pieces of small lumber (3 inches wide by approximately 1  $\frac{1}{8}$  inches thick) fit in between the top of the cross braces and span each section of the truss and appear to be nailed to the top chord. The plaster sits flush with these pieces, so it is likely that these functioned as screed boards to enable the plasterer to

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<sup>47</sup> Jacobs, James A. *Historic American Buildings Survey*, Wagner Free Institute of Science. HABS no. PA 6667, 2000.

<sup>48</sup> Carl W. Condit, *American Building: Materials and Techniques from the First Colonial Settlements to the Present*. Edited by Daniel Boorstin. (Chicago: The University of Chicago Press, 1982), 48.

create a smooth interface between the plaster and truss. These pieces are painted to match the ceiling and blend in with the plaster. To resist thrust, wrought-iron tie-rods are attached to the truss ends for reinforcement. The tie-rods are attached to bearing blocks set into the load-bearing brick walls. The bottom chord is set directly into notches cut into the bearing blocks.

Some of the trusses show signs of damage. Some show cracks on the underside of the bottom chords. Some show visible staining, presumably due to water. In some cases, the spliced ends of the truss jut out slightly from the plane of the chord. However, the structural engineer deemed them structurally sufficient to carry the load of the roof as well as any anticipated loads from wind or snow.<sup>49</sup>

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<sup>49</sup> Donald Friedman. Letter to W. Stivale, 19 September 2005



**Figure 13: Roof probe 2, showing intersection of the purlins, nailers and truss. Photo by M. Goeke, 2007.**

### *Purlins*

Knowledge about the placement of the purlins is based on archival information combined with observations from the roof probe. In bays where there are skylights, the purlins run just underneath the skylight frame, as indicated by the limited documentation of the renovation. Roof probe 2 shows a purlin spanning multiple bays, sitting in a one inch channel notched into the truss. The span length is unknown. Because they do span multiple bays, it is assumed that the purlins line up along the length of the building and are not staggered from bay to bay. Additional roof probes would be required to confirm the position and length of the purlins.

The purlins are placed 23 inches on center. They vary slightly in size, generally 2 ¾ inches wide and between 8 and 9 inches in height. In some places, shims were noted between the purlins and the nailers, perhaps to accommodate for the height difference from purlin to purlin. No wood rot was noticed in the six probes so the purlins appear to be in good condition.

### *Nailers*

Information about the placement and location of the nailers was also based on information from the roof probes. The nailers are approximately 2 ¾ inches in width by 1 ¼ inches thick and run parallel to the trusses. They are placed 16 inches on center from each side of the truss. It should be noted that the nailers are slightly larger than usually recommended. Like the purlins, the nailers generally appeared to be in good condition, with no visible wood rot.

Although spaced appropriately, the nailers contribute to a large amount of unkeyed areas. With 2 ¾ inches unkeyed sections every 14 5/8 inches, a significant portion (about 18%) of the ceiling is attached only via adhesion between the plaster and wood and therefore more vulnerable to detachment.

Verrall clearly addresses the importance of the framing support of plasterwork:

The importance of obtaining a good and even key for the plaster, particularly in ceiling work, has already been pointed out in discussing laths, and in this connection it is well to consider the effect that nailing lathing directly to supports may have on causing bad plaster work... it should be remembered that, apart from a small percentage from bonding, or adhesion, to the face of the lath – depending greatly on the roughness of the wood – the weight of the plaster is secured by that part of the mortar which turns over top of the spaces between laths. Owing to the shrinkage of

the lime, and the swelling and subsequent shrinkage of the lath, no bonding, of course, be looked for on the edges of the laths on either side of the spaces. Furthermore, where laths are nailed direct, as is often the case, to such plain surfaces, the plaster is merely pushed up against the joists without obtaining any key over these comparatively large areas.<sup>50</sup>

He suggests that in areas where keys will not form for two or more inches, the area be counter lathed.<sup>51</sup> Counter lathing, which consists of running lath strips perpendicular to the nailing member, provides for additional key formation in areas where no keys would form. However, no counter lathing is evident at the Wagner. If Verrall is correct, the presence of nailers of this width could compromise the integrity of the ceiling.



**Figure 14: Area of loss in Bay 2. A nailer abuts the top chord of the truss. They then are set 16 inches apart. Lath spacing, some too close together, is also visible.**  
Photo by A. Finke, 2007.

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<sup>50</sup> Verrall, 97.

<sup>51</sup> Ibid.

## *Lath*

Lath are nailed directly to the nailers, and run north/south. The lath are approximately 1 3/8 in. wide. Lath should be sufficiently spaced so that the plaster can form adequate keys, usually 3/8 in. In some probe areas, and in the area of loss, inadequately spaced lath is visible. Historic texts indicate that lath should run about 3 to 4 feet in length, be slightly separated to allow for movement, and should be somewhat staggered as to prevent long lath junctions which may crack. This could not be confirmed in the Wagner ceiling without removing plaster. There is speculation that some of the east-west cracks are caused by the lath ends. This is possible as the cracks appear to line up approximately with nailers, which is where the lath ends meet.

The lath that was inspected also appeared to be in good condition. In Probe 6, however, damage was visible due to warping and twisting of the lath. Probe 6 was over an area of water staining, so damage to the wood from water is likely. In some places, gaps exist between the lath and the key, perhaps from drying of the wood (or in combination with shrinking of the plaster). These small gaps between the plaster keys and the lath have implications on the stability of the plaster.



**Figure 15: Probe 2. Gaps between lath and plaster may indicate drying and shrinking of the wood. Photo by A. Finke, 2007.**

### *Wood Deck*

The tongue and groove boards of the roof deck are fastened to the top of the purlins, and run east/west. They are 4 inches wide and 1 inch thick, and bend to the curve of the ceiling. The tongue and groove joinery imparts additional structural support to the roof and ceiling framing.

### **5.3.2 Building Movement**

In 2005, Donald Friedman, P.E. of Old Structures, Inc. performed an analysis of the trusses to determine their capacity for carrying the roof load. While it was deemed that the trusses are structurally capable of carrying the load that may be expected of them, there does appear to be some movement in the walls that may



be affecting the cracking of the plaster.<sup>52</sup> Friedman concluded that the masonry walls of the building on which the trusses rest are rotating outward at different rates as a result of the elongation of the tie rods under load. As the dead load increases, the tie rods will lengthen and further push the walls out. Similarly, live loads like snow may temporarily do the same thing, potentially causing gradual but permanent tilt or damage to the walls. However, the amount of movement was not deemed to be dangerous for the size of the walls provided the masonry is maintained, as was recommended.

Though the walls were determined to be out of plumb, they are not uniform in their rotation. The exterior stucco, however, shows no visible damage, making it difficult to discern where there are large amounts of movement. Friedman noted that the condition of the plaster is not necessarily worse in areas of greater movement, which makes it difficult to correlate movement in the walls with damage to the walls and ceiling.<sup>53</sup>

If the structure continues to move, as is likely, through thermal and moisture cycling and changing loads from snow and wind, it is expected that the cracks may grow. Verrall warns that "in ceilings, it is useless to expect the completed plaster work to be free from cracks unless the joists to which they are attached are sufficiently stiff to carry their load."<sup>54</sup> He points to the 1/360 formulation for

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<sup>52</sup> Friedman, 4.

<sup>53</sup> Friedman, 2.

<sup>54</sup> Verrall, 96

determining maximum allowable deflection of spanning members, beyond which a ceiling is expected to crack under load.<sup>55</sup> In the specific case of the Wagner ceiling, (L=60 ft), this point is reached at a movement of about 2 inches.

While this may support an argument to replace the plaster, it also appears that the cracks could be providing a place for inevitable movement in the ceiling. In this way, the cracks could be acting as expansion joints that the ceiling is otherwise lacking. The fact that the building is expected to move does not mean that the cracks cannot be stabilized in such a way as to limit their growth while retaining their ability to move with the structure.

## ***5.4 Archival Research***

### **5.4.1 Alterations and Maintenance**

Records indicate that in 1876, the building's newly installed tin roof had been damaged in a tornado, and a rainstorm a few days later caused extensive interior damage. The roof was repaired, but it was damaged again in 1878 following another rainstorm.<sup>56</sup> It is unclear how or when the roof was repaired after the second storm, though repairs on the tin roof were noted during the 1880s renovation.

Major changes to the exhibit hall ceiling occurred during this renovation campaign. Re-plastering of the ceiling began in 1886. New tie rods were installed

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<sup>55</sup> Ibid.

<sup>56</sup> Jacobs, 8.

on the trusses to increase the trusses ability to support the total load of the ceiling.<sup>57</sup> The exterior was stuccoed, as was originally intended, which also served to protect the exterior brick already showing weathering.

The Wagner archives contain a document by Collins & Autenrieth that details many of the alterations done during the renovation period.<sup>58</sup> While it is only a specification, it is likely that many of these alterations can be accounted for either in receipts or changes to the building itself. Several items of note may be of interest as they relate to the structure or performance of the building. One is the direction to raise the flues on the roof and reset the chimney pots, both of which are located along the edge of the load-bearing brick walls. Changes to the walls are important to note as the walls provide support for the trusses. Work done along the top of the walls may have affected the capacity of trusses to transport load from the roof to the walls or altered the load path along the walls. The specifications directed that the stack for the steam heating boiler be built on the west side. It also called for the repair of 1/3 of the tin roof, and replacement of 2/3 of the roof as well as replacement of the gutters and spouts with ones made from galvanized tin. A drawing of the skylight is included in the specifications, detailing how the skylight fits into the overall structure of the roof

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<sup>57</sup> Estimate, Building Improvements, 1885-1891. ARC 91-035, folder 1. Wagner Free Institute of Science Archives.

<sup>58</sup> Collins & Autenrieth, "Specifications for the Improvements of the Building of the Wagner Institute," March 26, 1885. Building Improvements, 1885-1891. ARC 91-035, folder 34. Wagner Free Institute of Science Archives.

along with details about the size of the glass, mullions and sash, indicating that the skylights may have been altered during this period.

Receipts from the Wagner archives indicate that the new plaster ceiling was put on in 1886 and the plumbing and drainage work was performed in 1887. The drainage work may have been a response to water infiltration visible in the ceiling or walls, or it may have been necessary work that was delayed, leaving the plaster ceiling vulnerable. According to receipts, further alterations to the roof's drainage system, including improving the conduction of rain runoff, were completed in 1892.<sup>59</sup> Roof drainage is of particular importance as water can cause significant damage to materials like plaster. Alterations may have been undertaken because of known water infiltration issues, thereby indicating the vulnerability of the plaster at the time.

The firm of Hewitt and Hewitt was hired in 1901 to design the library addition. This last phase of construction is believed to have limited physical impact on the larger building, except for the few adjustments made to the west portion of the original building where the two meet. The two lower windows on the west side were removed and extended to provide doorways to the addition. The upper windows were shortened and their sills moved up slightly to accommodate the roof of the library addition.<sup>60</sup> Because the walls impact the

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<sup>59</sup> Building Improvements, 1885-1891. ARC 91-035, folder 2. Wagner Free Institute of Science Archives.

<sup>60</sup> "Wagner Free Institute of Science." G. W. & W. D. Hewitt, Architects, 1/14/1901. Pew Museum Loan - Wagner Free Institute of Science Collection, Athenaeum of Philadelphia.

function of the roof, any changes to the walls may have induced damage either in the wall or the roof. If the lower window opening were widened for the doors, load transport would change. The addition's walls may provide additional support to the west wall of the main building, but the change also means that the altered area of the existing wall may thereafter move differently from the walls around it.

Archival documentation shows that there were continual problems with leaking in the roof of both the Institute building and the library addition. Problems with the roof and exterior stucco of the addition were noted as early as 1903, which may have caused excessive water leakage into the original building, particularly near the two bays where the two buildings are joined. Maintenance records of the Institute building show continued problems with leaking skylights which were serviced in both 1913 and 1924. Archival files from 1913 were too damaged for use, so the details of those repairs are lost; however, an estimate from 1912 indicated that repairs needed to be made to the roof and gutters of the main building and the library. An estimate from January of 1924 included projected costs for replacing part of the west side of the tin roof ; repairing leaks and replacing broken glass in the skylights; repairing holes in the roof; and coating and painting the gutters and downspouts.<sup>61</sup> The estimate was approved suggesting that the work was carried out, but the exact date of the repairs is

unknown.<sup>62</sup> The probes from 2007 revealed layers of roofing material in some sections, indicating years of patching and repairs. Patching is visible around the top of the skylights.



**Figure 16: Skylights from the roof. Note the patching around the edge of the skylights. Photo by A. Finke, 2007.**

In 1924, several people reported on cracks in the building interior. It appears that the Board of Trustees asked both a carpenter as well as an engineer to look at what were referred to as “museum wall cracks” and “settling of floors under partitions in the reference library.”<sup>63</sup> The wall cracks were located on the second

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<sup>61</sup> Estimate from Robert C. Williams. Minutes of the Board of Trustees of the Wagner Free Institute of Science, 1924. Wagner Free Institute of Science Archives.

<sup>62</sup> Bill from Robert C. Williams, unknown date. Records of the Wagner Free Institute of Science, 1885-1949. ARC 90-001, box 17. Wagner Free Institute of Science Archives.

<sup>63</sup> Letter from John Duncan, Carpenter and Builder. Minutes of the Board of Trustees of the Wagner Free Institute of Science, February 1924. Wagner Free Institute of Science Archives.

floor balcony ceiling in the Exhibit Hall. The carpenter and engineer attributed the cracks to vibrations from the trolleys and trucks passing the building.

While no one was particularly alarmed at the presence of the cracks, the experts recommended papering over the cracks to see if they were active.<sup>64</sup> If their advice was followed, it was not documented. Exterior cracks in the arches over the windows are also noted and were attributed to the initial movement of the building as well as the same increased vibrations associated with the cracks in the second floor balcony. The carpenter additionally stated that the structural defects of the building are common in most buildings of significant age.<sup>65</sup> It does not appear that the Institute was greatly concerned with these cracks as follow-ups to these assessments were not documented, and in May of 1924, it was recommended that Trustees postpone “work on the Institute Building (without disadvantage)” to the fall.<sup>66</sup>

Despite all of the reported roof damage and water infiltration incidents, there have been only minor repairs and treatments on the plaster ceiling. Nevertheless, the ceiling has remained intact and serviceable throughout its 120 year history.

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<sup>64</sup> Letter from Samuel Wagner. Minutes of the Board of Trustees of the Wagner Free Institute of Science, February 1924. Wagner Free Institute of Science Archives.

<sup>65</sup> Letter from John Duncan, Carpenter and Builder. Minutes of the Board of Trustees of the Wagner Free Institute of Science, February 1924. Wagner Free Institute of Science Archives.

<sup>66</sup> Letter from S. J. Skidmore, Trustee. Minutes of the Board of Trustees of the Wagner Free Institute of Science, February 1924. Wagner Free Institute of Science Archives.

## 5.4.2 Environment

The Franklin Institute has recorded weather data for Philadelphia dating back to 1872, which gives a general picture of the type of exposure buildings in Philadelphia experience.<sup>67</sup> The climate in Philadelphia is generally mild, with average annual temperatures ranging between 50°F and 58°F. Average summer temperatures have reached the high 70s, while average winter temperatures have dropped as low as 28°F; temperatures can be more extreme within a day. Rainfall tends to be consistent, between three and four inches per month, throughout the year. Winter snowfall averages between 18 and 28 inches, but extremes as high as 65.5 inches were recorded in 1995-96, and 55.4 inches in 1898-99. The possibility and frequency of extreme snow and wind is of particular concern for the Exhibit Hall ceiling as any increased load, even temporary loads like snow and wind on the roof may impact the ceiling. Ongoing or frequent changes in the load, causing movement of the system, could lead to material fatigue, particularly in the fairly brittle plaster.

Temperature range is an important factor to consider, particularly for the design of this plaster ceiling. Heating and cooling cycles cause all materials to expand and contract. Plaster systems are vulnerable to temperature cycling because they are made from different materials that expand and contract at different rates. This has great implications for the Wagner as the ceiling is also

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<sup>67</sup> <http://www.fi.edu/weather/data2/index.html>



the roof. The roof will experience a greater temperature variation than the plaster underneath, causing greater expansion and contraction of the wood members. Moreover, each wood member type (truss, purlin, nailer, lath) will move at different rates depending on their width, length and wood type. Joined together as a system, differential movement is inevitable. Since the plaster is adhered to this wood system, it is almost inevitable that the plaster will crack.

The Philadelphia area also experiences high humidity conditions in summers. Such conditions along with periodic high temperatures further expose wood members and the plaster to moisture cycling with attendant dimensional changes.

The Wagner is oriented on a N/S axis turned slightly east, following the street pattern of Philadelphia. The front entrance is located on the north end of the building, and all additions to the building were constructed on the building's west side. The orientation of the building is of particular importance when considering environmental factors like solar radiation and wind. Solar radiation can be both beneficial and harmful to building materials. Solar radiation causes increases in the temperature of materials, which can lead to thermal expansion and contraction as discussed above or, more seriously, UV degradation of materials like asphalt. The materials observed on the roof of the Wagner included an asphalt material, which in some places was apparently repaired.

On the positive side, solar radiation as well as wind also can help dry out materials that have become wet from precipitation, thereby eliminating harmful water from active movement through the materials. The Wagner roof has had ongoing issues with water infiltration so solar radiation provides much needed drying. The altitude and azimuth of the Wagner building determine the expected solar radiation for different times of year. In general, the south side of buildings gets the most solar radiation as this is where sun is at its highest. In the winter, the north side of the building gets virtually no solar radiation as the sun rises and sets in the southeast and southwest. During the winter, snow and the lack of sun on the roof could lead to longer loading as well as the introduction of moisture. This has implications for the building materials of the roof, the roof framing system and the plaster ceiling.

Wood members used in construction are generally dried before use, but are never fully dry. The recommended moisture content of wood for construction is between 15 and 19%.<sup>68</sup> Because the wood used in the ceiling/roof is exposed to high temperatures, much of the residual moisture may have evaporated. Moisture loss will cause dimensional change in the wood as it shrinks with the loss of water. This could explain the fairly large gap between the lath and the plaster – the lath, in fact, has shrunk since the plaster was applied.

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<sup>68</sup> *Wood handbook: wood as an engineering material*. General technical report FPL; GTR-113. (Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1991), 12-5

### 5.4.3 Building Context

When the Wagner was first built in the 1860s, it existed in relative isolation, far from the density of Center City. The city was quick to catch up to the Wagner, and by the 1880s, every block in immediate proximity to the building was built upon with three to four story brick row houses. Essentially, the area around the Wagner remains the same today, with mostly three story brick row houses, though some have been lost to neglect. Minimal construction has occurred around the building since the installation of the plaster ceiling.

During its early life, the Wagner existed in a hub of public transportation. Ever since the expansion of the city north, 17th Street has been a trolley and later a bus route, connecting center city to Olney. In the 1870s, the streetcar system had several routes near the Wagner. An 1870 Railway Map of Philadelphia shows that the Wagner lies on the 17th and 19th street car lines, and within four blocks of the Continental, Empire and 13th and 15th Lines.<sup>69</sup> An 1899 Union Traction Company map shows several of the same routes, as part of the Philadelphia Traction Company, as well as several Traction Company buildings within a few blocks.<sup>70</sup> The 1910s and 20s saw the building of the Broad Street subway, which opened in 1923. This environment, particularly the 17<sup>th</sup> Street

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<sup>69</sup> Railway Map of Philadelphia to Accompany Westcott's Guide Book to Philadelphia, 1870. Free Library of Philadelphia.

<sup>70</sup> Union Traction Company, 1899. Free Library of Philadelphia.

Trolley line, could have caused a significant level of vibration. Continued vibration can take its toll on plaster by weakening plaster keys.<sup>71</sup>

Settling of the building is also a potential explanation for crack formation. Cohesive soils can compact under the weight of a building over time, resulting in wall and foundation movement. When the parts of a building move at different rates, different stresses occur and can result in cracks. If movement is significant enough to compromise the stability of the structure, the cracks can be viewed as a warning signal. Often, they are not of great concern, as noted by the Wagner's carpenter in 1924.<sup>72</sup> Structural monitoring of the building over time is required to assess the relationship between building movement and the formation of cracks.

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<sup>71</sup> Bernard Feilden, *Conservation of Historic Buildings*. (Oxford: Architectural Press, 1982.) 158.

<sup>72</sup> Letter from John Duncan, Carpenter and Builder. Minutes of the Board of trustees of the Wagner Free Institute of Science, February 1924. Wagner Free Institute of Science Archives.

## 6.0 Analysis

The previous assessment offers some connections between the cause and effect relationships responsible for loss from the plaster ceiling, but there is no clear definition as to the cause of the problem. Deficiencies found in the analysis of the fallen sample from Bay 2 (the low sand to binder ratio in the scratch coat, the thinness of the scratch coat) and the insufficient keys observed in the roof probes were clearly present in the ceiling since it was installed in 1886. Despite these deficiencies, the ceiling lasted for 120 years before any loss occurred. This suggests that these deficiencies must work in conjunction with other variables (damaging conditions or situations) before loss occurs and that preserving the ceiling is still a viable as well as desirable option. Key to a successful analysis is determining which interacting variables are important to evaluate with the tools at hand. One can develop a long list of potential variables that may or may not influence the vulnerability of the ceiling to loss. Careful selection of the critical variables must develop out of disciplined and educated assessment of the factors affecting the ceiling. In the specific case of GIS analysis, only visible variables of a spatial nature can be used as input, which points out one of the limitations that is associated with map analysis of this type. This limitation is far outnumbered by the benefits found in the way a GIS software like ArcGIS can represent the visible data in new and unique ways. Determining which visible data to include can be

difficult and needs to be decided using the other assessments and research discussed earlier.

Future loss is the main concern with the plaster ceiling, so detachment of the plaster surface from the lath is of primary importance. Once the plaster has detached from the lath, there is a high risk that the plaster could fall. This problem is exacerbated by cracking, which divides the plaster into panels. If a high percentage of broken keys or detachment exists within panels, it is probable that the entire panel may fall. The size of the panel may have an impact on loss and detachment, and should be a consideration in analysis.

While detachment may be of primary concern, it is difficult to assess in the field, as it is a blind condition occurring on the opposite side of the plaster surface. Tap techniques have proven to be useful in related applications, but were not useful here because measurements are subjective and therefore difficult to compare between two observers or two situations. Thus, the visible conditions are the only real starting point for analysis.

Displacement represents areas where a certain degree of detachment has already occurred, and should be considered as another important variable. For the purpose of this analysis, displacement is used as an indicator of potential to detach. Examining the relationship between crack size and displacement may lead to an understanding of where detachment may occur.

Another important variable is water infiltration. Water damages the plaster by weakening the binder through dissolution or otherwise weakening the cohesive forces in the plaster mix. It can also adversely affect the wood framing that supports the plaster, causing warping, rot, corrosion of fasteners, and dimensional changes from wetting and drying cycles. Weakened plaster keys or water damaged wood elements could explain some of the cracking. As a fluid, water absorbs into the wood and plaster substrates and excess water will flow to low points in the structure. Water will pool in flat areas, like the top of the arch near the skylights where the ceiling is relatively flat. Prolonged and repeated exposure to water could cause severe damage to the impacted area. Likewise, the arch of the ceiling allows water to flow down the length of the ceiling and through cracks perhaps affecting a larger surface area.

Historic documentation reveals a history of roof leakage and visible evidence of roof patching. The spread of water stains on the ceiling indicates that the skylights allow much of the water infiltration, particularly at the corners, and the roof probes confirmed that the poor condition of the plaster keys and the lath is likely related to water infiltration. This condition is an important factor to consider when looking at threat. Thus, proximity to visible water staining as well as areas of known water entry will be important variables.

For this work, two types of separations found on the Wagner ceiling were defined: "one-sided," where the plaster has separated from the building element

which borders it; and “two-sided,” where cracking has occurred within the continuous plaster itself. Both were quantified as small, medium, and large. One-sided separations occur where the plaster borders different material, like wood. The areas of plaster located along these wooden elements have inherent vulnerabilities as it is the interface between two vastly different materials. The wood is likely to shrink considerably upon reduction in moisture content, resulting in gaps (cracks) between the plaster and wood. Additionally, the trusses support the ceiling and may experience significant differential movement as a result of the change in loading and temperature and moisture cycling. This action will break the bond between the plaster and truss, resulting in a one-sided separation. One-sided separations were not noticed along the skylights and roof hatch, perhaps because of the molding around those elements. The plaster appears to have been applied to the edge of the skylight and hatch frames, with the molding applied on top of the plaster. This could explain why no separations were found along these elements even though they likely experience movement. The molding may be providing additional support to the plaster edge along those elements and may explain why the small panel of plaster in between the skylight and the loss in Bay 2 has not fallen.

While one-sided separations can have displacement, they were treated separately from two-sided cracks because of their inherent differences. In the following analysis, all cracks are two-sided unless otherwise noted.



Since the cracks are the most severe condition as well as a visual condition that can contribute to loss, they are deemed highly significant to the analysis. Cracking can be viewed as either a cause or effect of deterioration. In the first case, the cracking could cause loss or detachment. Cracks that occur through plaster keys weaken the mechanical bond of the plaster surface and its weight could be enough to cause detachment. Also, cyclical movement could cause material fatigue along the cracks. If cracks are extensive and severe enough, causing the keys to break, the existence of cracking could explain the loss in Bay 2. On the other hand, cracking could be an effect or symptom of other mechanisms acting on the ceiling. Cracking may result if these factors damage or weaken the plaster and cause detachment. In either case, the cracks could be adding to any existing vulnerability by providing faults along which further damage can occur.

Assuming that cracking is causing the detachment/loss, there are several variables to consider when attempting to predict areas of threat. First is the cracks themselves: if they exist in areas that are considered to be a site for future loss, the density and location of the large and medium cracks are of the highest concern. The small cracks, though widespread, were identified as surface cracks and are assumed to not permeate all layers of plaster. Because of the pattern of the cracks, the structural framing of the ceiling is also a concern. Proximity to the nailers, purlins, trusses, and wall edges are possible considerations when

determining threat as they appear to be related to the cracking pattern. Building movement as well as thermal and moisture cycling could be acting on these wooden elements, causing cracks in the plaster. The trusses are a particular concern because of the interaction of multiple sizes and types of wood. The lumber placed in between the cross-bracing could move differently than the truss, as can the nailers and lath. Truss movement will impact the purlins since the purlins are set into a notch in the truss. The variability of movement at the junction between the plaster and truss could cause serious weaknesses in the plaster. Another consideration is existing displacement. Displacement occurs mainly along the large and medium cracks and indicates movement of the plaster out of plane. In these locations, detachment is either already existing or could occur at any time.

On the other hand, if it is assumed that the cracking is a symptom of detachment, a different set of variables should be examined to predict threat. Detachment could be caused simply by the materials themselves, for example the low aggregate content in the scratch coat (as found in the fallen sample) or the method of application, resulting in insufficient keys. The probes revealed that many of the keys were never sufficiently formed, resulting in many areas of the ceiling without mechanical attachment to the lath. The keys that did not form properly could drop from in between the lath. If a large enough area dropped, the plaster would crack. Again, this is a blind condition, like detachment,

representing an unknown that cannot be used as a variable in the GIS analysis. It is important to consider it a possible widespread threat to the ceiling; however, considering the age of the ceiling, it is likely not a problem by itself but could be working in conjunction with other mechanisms. Material problems, however, are not spatial variables, and cannot be analyzed using GIS. They do, however, work with GIS as a way to come to stronger conclusions, and are important to consider when defining causal relationships.

What can be mapped is the location of the nailers, which represents areas on the ceiling where keys were never formed. These areas can be considered areas of threat because they also lack the mechanical attachment with the framing. Similarly, the age of the ceiling indicates that the presence of nailers alone does not necessarily indicate imminent threat. Of particular concern, however, are the nailers along the truss edge, where the plaster is both thicker and lacking keys and where different materials meet. This also represents a location where loss has occurred. Similarly, while dropping plaster from insufficient keys cannot be mapped, displacement can. Displacement may be occurring along cracks in areas of insufficient keys, indicating a vulnerability to loss.

## ***5.1 GIS Analysis***

Analysis with ArcGIS provides two definable ways of looking at the conditions. One, it can quantify conditions to provide numerical data about the

extent of conditions which can then be compared among the different locations on the ceiling. Using the tabular information within each ArcGIS shapefile, numerical values can be calculated to use for comparative analysis. These numbers can be used independent of their source maps.

Two, it can provide visual representations (maps) of the conditions. These maps show the spatial relationships of different conditions to each other, and can show the relationship of a specific location of a single condition to a different location. The visual images can then be mathematically combined to create new images that reflect the added effects of the conditions on the ceiling. All maps can be found in Appendix A.

### **5.1.1 Quantitative Calculations**

The ceiling data were quantified so that conditions could be understood in proportion to its surface area. The fields of plaster in each bay vary slightly in area, with Bay 1 being the largest at 146,006 square inches. Bay 1 is an end bay, framed by a truss on the south end and an exterior wall on the north end which may explain the slightly larger surface area. The areas of the skylights were subtracted from the total area of bays 2 and 4, leaving 118,944 and 112,563 sq. in. of plaster, respectively. Bays 3 and 5 were close in size at 134,645 and 133,137 sq. in., respectively. The area of plaster loss from 2003 is 1,617 sq. in. —1.35% of Bay 2 and 0.25% of the combined five bays. Combining total loss with the area of repair, where the circumstances of the loss are unknown, accounts for 0.55% of

the five bays. Assuming that the remaining four bays are comparable in size, loss accounts for only 0.30% of the entire ceiling.

#### *Crack Distribution*

Cracks of all sizes were quantified by length. As it is difficult to determine the beginning and end of cracks, the overall length of cracks was used for comparison rather than the actual quantity or “count” of cracks. The overall length of cracking in all five bays totaled 38,594 inches. These cracks were distributed fairly evenly over the five bays (Map 4: Cracks by Bay). Bay 1 has the highest amount of cracks at 24% of the total, but it is also slightly larger than the other four bays as it is an end bay. The bay with the smallest length of cracking is Bay 2 at 16% of the total. When expressed in proportion to area, Bay 2 is only slightly less than the other five bays which all contain approximately the same amount of cracking. Cracking as an overall condition appears evenly distributed across the five bays assessed.

#### *Crack Size*

Crack size was also fairly evenly distributed throughout the bays with some notable exceptions (Map 5: Crack Distribution by Bay). Overall, large cracks made up the smallest percentage of cracks (14%), followed by medium (41%) and small (45%). Large cracks ranged from 10 to 24 % of the total cracks per bay with the highest percentage in Bay 2. The number of cracks in this area makes it a potential area of weakness since the plaster that was lost in 2003 was lost from

Bay 2. It has the lowest amount of total cracking, but the largest amount of large cracks. Since the number of large cracks showed a great dissimilarity to the medium and small, which are close in total length, the large cracks may be occurring for different reasons than the medium and small cracks.

The length of medium and small cracks varied by bay. Medium cracks in Bays 2 and 5 exceeded small cracks, a difference from the overall distribution of crack size. Over 50% of cracks in Bay 5 are medium cracks, and 40% of the cracks in Bay 2 are medium cracks. Small cracks out-populated medium cracks in Bay 3, 55% to 35%, Bay 4, 41% to 46%, and Bay 1, 40% to 50%. Small cracks, while they represent the most cracks in linear inches, generally are the shortest in length, often occurring at the ends of or branching off from large and medium cracks. This implies that small cracks may eventually turn into medium and large cracks, and may be detected by a monitoring program. If small cracks lead to medium and medium lead to large, there is a prioritization which may allow small cracks to be excluded at this time.

At first glance, Bays 2 and 5 appear to be the most different in the overall distribution of cracks. Bay 2 has a high percentage of large cracks and a small percentage of small cracks. 29% of all of the large cracks are in Bay 2 but only 13% of small cracks, and 16% of medium cracks, slightly less than expected if the cracks are evenly distributed. Bay 5 has a large percentage of medium cracks - 25% of all of the medium cracks. Bay 5 is the central bay in the ceiling, which

may explain why the crack size distribution is different from the other bays. The irregular distribution in Bay 2 is even more notable since it is the location of recent loss.

#### *Crack Direction*

The regularity of the cracking pattern suggested that there might be a relationship between cracking and direction of cracking. Cracks were divided into those running in three orientations: approximately north-south, east-west, and diagonally. Cracks running north-south may be of greatest concern since they run in the same direction as the lath and the plaster keys. Long lengths of broken keys could weaken the attachment and lead to loss.

Cracks running east-west are perpendicular to the lath and appear to be of less concern because they do not lead to complete loss of key attachment. However, these cracks do run parallel to nailers, where plaster attachment is already weak since it is not keyed. As such, cracks in these areas may be more susceptible to loss.

In general, east-west and north-south cracks are evenly distributed, both making up about 35% of the total length of cracks. The remaining cracks run diagonally. The distribution of sizes in both the east-west and north-south cracks is similar to the distribution of all cracks, although medium cracks slightly outnumber small cracks in both cases. The east-west cracks were distributed fairly evenly throughout the five bays, with Bay 2 having a slightly lower

number than the other four bays. The fairly even distribution of crack direction in the bays accounts for the appearance of a uniform crack pattern. The number of north-south cracks, however, tended to be higher in Bays 3, 4, and 5. Accordingly, diagonal cracks are found in a higher percentage in Bays 1 and 2: 38% of the diagonal cracks are in Bay 1, and 25% are in Bay 2. The lowest are in Bay 4, only 9% of the total.

The formation of diagonal cracks in Bay 1 could be attributed to several things. One, it is an end bay framed by a truss on the south end and a brick wall on the north. The intersection of the two brick walls at the corners of the building may influence how the ceiling of Bay 1 moves, and may result in diagonal cracks. Racking of the building would also cause diagonal cracks. Since only half of the total ceiling was assessed, it is difficult to determine if the building is racking. This factor should be examined in future monitoring. As Bay 2 sits next to the end bay, it may also be affected by the end movement of the building, particularly if the entire building is racking and could explain the higher percentage of diagonal cracks. Diagonal cracking of the northwest corner of the second floor balcony ceiling was noted which may be a result of the same building movement. Truss movement could also account for diagonal cracking. Differential movement of the trusses could result in shear strain in the plaster, which would manifest itself in diagonal cracks. This could be confirmed while monitoring crack areas and trusses.



Large cracks generally run either north-south or east-west (39% and 41% of all large cracks). Medium cracks show a similar pattern, with 40% of all medium cracks running north-south and 38% running east-west. Small cracks made up the bulk of the diagonal cracks at 51%. This is understandable, as small cracks tend to form as branches off larger cracks. It would be valuable to determine if these small cracks are growing into medium and large cracks through crack monitoring.

### *Displacement*

Displacement was recorded on both “one-sided” cracks (separations) and “two-sided” cracks. As discussed in section 5.1.1, displacement is out of plane movement of the plaster. Displacement along one-sided cracks has different implications than displacement along two-sided cracks. Because one-sided cracks occur along a truss edge, movement of the plaster can result from the three different types of movement previously outlined. It is impossible to know which kind of movement is occurring when observing only the underside of the plaster. In all cases, considerable movement of the plaster is deemed to be a problem as continued movement weakens the surface.

It is likely that the plaster originally lined up with the bottom of the screed boards wedged above the cross-braces and bonded to the bottom of the upper chord of the truss. Therefore, when measuring displacement along the truss, the bottom of the screed board was used as a baseline, which is simply referred to as

the truss. Displacement measurements included both movement of the plaster below the line of the screed board as well as above. In Probe 2, an area of high displacement, observations from above indicated that the plaster was, in fact, moving out of plane from the nailers, the lath and the truss.

Within the entire 5-bay survey area, 8,453 linear inches of displacement of all types and sizes was recorded (Map 6: Displacement). There was a significant amount of displacement of one-sided separations along the trusses. In fact, all displacement over 5 mm is found along the truss edge, except for one 10 inch length of displacement over 10 mm in Bay 1 located near the roof hatch, which accounts for 24% of the total displacement. There are much fewer lengths of large displacement than small. Displacement over 10 mm comprised only 5.5% of the total. Displacement less than 2 mm comprised over 50% of the total of all displacement. It is important to note that 96.5% of displacement within the bays, as opposed to along the trusses, is less than 3 mm in size.

To understand the extent of cracks associated with displacement, all cracks and separations that fell along areas of displacement were quantified. 38% of those cracks were large cracks, and 58% were medium cracks. More importantly, a majority of the large cracks have areas of displacement – 70% of all large cracks have some displacement along their length. It appears that large cracks tend to displace, which implies that large cracks are potential areas of vulnerability.

### *Water Staining*

Water staining is visible on only 6% of the entire surveyed area (Map 7: Water Staining). Although this is a small percentage, it is still a significant concern as water is one of the most damaging agents to plaster and wood. Water staining is spread unevenly throughout the ceiling. Bay 4 has the highest percentage at 45% of the total. Most of this staining is concentrated on the east side of the bay. The skylight is likely responsible for much of the water staining.

Water staining on the surface of the plaster does not necessarily indicate damage to the plaster support directly above it. The water may be only affecting the top layer of the plaster by leaking through cracks and running down the exterior plaster surface. However, results from the roof probes do associate lath and key damage and visible staining underneath. To examine the relationship between water staining and cracking, cracks were clipped to the area of water staining to quantify the length and types of cracks found within these areas. Almost 9% of all the cracks fall in the area of identified water staining, slightly higher than expected based on the surface area of the staining. However, almost 14% of all of the large cracks fall within this area of water staining that represents only 6% of the ceiling. (For comparison, only 8.5% of the medium and 8% of the small cracks fell into the same area.) Whether these large cracks are caused by the water migration is unknown. However, the above relationship is of concern because the areas showing visible water staining are more likely to be in a

compromised state and vulnerable to loss. Thus, large cracks in areas of water staining should be monitored.

### *Nailers*

The nailers are key framing elements that sit behind and run perpendicular to the lath and cover 18% of the entire surveyed area. The plaster covering the nailer areas does not form keys and is therefore more weakly attached to the lath than the remainder of the ceiling. Also, lath ends at the nailers which may also weaken the plaster attachment. To determine how the cracks might relate to the nailers, a buffer of one and a half inches was created around the estimated location of the nailers to accommodate for imprecise construction. This buffer zone covers 39% of the ceiling and contains 49% of all of the cracks, indicating a relationship between the nailers and cracking (Map 8: Cracks within 1 ½ in. of Nailers). Moreover, the large cracks appear in slightly higher quantities, as 52% of all large cracks fall within this area. Thus, the location of nailers do appear to contribute to the visible conditions on the ceiling. However, if there was a problem with the nailers as an element, one would image all of the nailers having cracks. As of yet, there is no clear explanation as to why the cracks only appear at approximately every third nailer. The suggestion that the lath ends could be causing the cracks is certainly valid. Because of the even crack distribution throughout the five bays, and the even distribution of east-west and north-south crack, there is also a possibility that the cracks formed quickly and are acting as

expansions joints to relieve stress from movement that would occur ceiling-wide. Because of the age of the ceiling and the limited area of loss, it appears that at the locations of nailers, vulnerability is heightened particularly when combined with other damaging conditions which may further compromise the already weak attachment.

### *Trusses*

The trusses are a source of most of the one-sided cracks (separations) found on the ceiling. In addition, many two-sided cracks begin (or end) at the trusses. Truss movement may also contribute to the formation of two-sided cracks along its edge. When considering the effects of the truss on the ceiling, both types of cracks need to be considered. To quantify two-sided cracks that may be occurring as a result of movement from the truss, a buffer was created around the truss. A buffer size of 3 ½ inches was chosen because it is about 50% of the size of the truss, a ratio similarly used to quantify cracks near the nailers.

There are over 6,800 inches of cracks found near the building trusses. The combined length of two-sided cracks and one-sided cracks (separations) found along the trusses make up about 15% of all cracks found in the five bays. Both large and medium cracks are found along the trusses, but large cracks make up almost 95% of the total. This is not unexpected as the plaster and the wood will move differently and separate along the truss line. Moreover, no keys are found in this area because a nailer butts up against the truss above the lath. Thus, the

truss edge is a weakness area based on the number of large cracks, the unkeyed lath and the attendant displacement.

The distribution of two-sided cracks located near the trusses fall into a pattern common to the rest of the ceiling, but with a slightly higher percentage of large cracks: 20% large, 39% medium and 41% small. This may be of concern as the plaster in the areas along the trusses is believed to be more vulnerable to loss because of the reasons just stated. The presence of large- and medium two-sided cracks in this area may weaken the stability of the plaster because it appears to get divided into plaster panels (described below), which may be more vulnerable to failure because they are separated from the plaster around them. The loss in 2003 occurred along a truss edge and the piece possibly was isolated by existing large or medium cracks. The southern edge of the plaster around the fallen piece falls in between a large crack and shows a significant amount of dirt, indicating that a large crack likely existed there. Further, any small cracks occurring at this truss edge are impacted by truss movement and may gradually increase in size.

#### *Plaster Panels*

Cracks visually divide the ceiling into plaster islands or panels resembling a jigsaw puzzle. However, the cracks are not necessarily as uniformly connected throughout the bays as one may think from direct observation, indicating that they may not be acting as independent units. Panel size can be explored by

defining the plaster panels as discrete shapes and examining their distribution and size.

There are two ways to define the plaster panels. In one case, only medium and large cracks define the panels (Map 9: Panel Size by Large and Medium Cracks). Because small cracks were defined by the conditions assessment as cracks that do not go through all plaster layers, they may not represent cracks that isolate panels. Large and medium cracks, however, are assumed to go through all layers and thus are locations of separation within the plaster that may act independently. When using the large and medium cracks only to divide the ceiling, panel size appears related to location on the barrel vault.

There are 241 of these panels averaging approximately 2,600 sq. in. (18 ½ sq. ft.) in area. Very large panels concentrate in the center of the bays. The largest panel is over 71,000 sq. in. (almost 500 sq. ft.), located in Bay 2. Two other large panels are located in Bay 1, also in the center of the bay. Both are about 43,000 sq. in. in area and are separated by several medium-sized panels. In the bays with large central panels, smaller panels line the edges. This is expected as the medium and large cracks tend occur near the walls and may be a result of wall movement. Bay 5 does not have any large panels (over 12,000 sq. in.), unlike Bay 3 which is also a bay with no skylight. Bay 5 is the center bay, which may be subjected to unique stresses, resulting in larger panels. Bays 2 and 4, both skylight bays, resemble each other, with small panels on the West side of the

skylight and large panels on the East. The west side may experience greater temperature variation from solar radiation, thus causing expansion and contraction of the wood. Water staining does not appear to correlate with panel size. Displacement occurs along an edge of 172 of the panels, 71% of the total panels. The presence of displacement is consistent with the fact that it is typically found in areas with medium and large cracks.

In the other case, all cracks can be used to define the panels (Map 10: Panel Size Defined by All Cracks). Since it is only assumed that small cracks do not go through all layers, it may be reasonable to use them to define the panels. Additionally, crack propagation is not yet fully understood, but it is reasonable to conclude that small cracks may eventually grow into medium or large cracks. At the very least, small cracks are weaknesses in the plaster surface. If the plaster panel dropped along one edge, the plaster may snap along that weakness.

Using all cracks to define the panels results in the appearance of over 780 panels. These range in area from over 8,500 sq. in. to less than 3/16 sq. in., with an average area of about 815 sq. in. (5 ½ sq. ft.). The majority of these panels are larger in area than the loss that occurred in Bay 2 in 2003. About 120 of these panels appear along the truss edges. Only two panels exceeded 8,000 sq. in. (in Bay 2 and Bay 4) and both have an edge along a truss. Panels between 4,000 – 6,000 sq. in. occur in all five bays. Of the 22 panels of this size, 13 occur on truss edges, and three along the north wall. Panels between 2,000-4,000 sq. in. account



for another 48 of the 120 panels along the truss edges. Assuming the truss edge does represent an area of weakness, these panels may be at risk of falling. One of the largest panels is located in the area of water staining in Bay 4 and may be at risk. The 39 panels with areas 1,000-2,000 sq. in. appear to be randomly spaced throughout the ceiling and don't appear to correlate with edges, centers, or locations within a bay. None of the panel sizes appear to correspond regularly with water staining. 374 of these panels have some form of displacement along their edge, 48% of the total. Since very few small cracks show displacement, this is expected.

It is unclear what effect the size of the plaster panels may have on the stability of the ceiling. Large panels may be less inclined to fall since they theoretically have more keys than smaller panels spreading the load of their weight over a large area. However, they are heavy and if these large panels are located in areas of damaging conditions, the entire panel may be especially weakened. Smaller, lighter panels have fewer keys for attachment, so damage to only a few keys could result in detachment. The area of loss was a medium-sized panel and appears to be bordered by a large crack opposite the truss separation. The plaster on the east side of the same skylight shows extensive displacement, but has not fallen. It is much larger than the lost piece which may help to keep it in place. The relationship of panel size and crack size may have implications on the potential for future loss but is still not fully understood.

### 5.1.2 Spatial Calculations

The Spatial Analyst extension allows for the creation of raster maps based on new parameters, namely density and distance. Using the line and point data derived from the AutoCAD conditions assessment, raster maps can be created to illustrate the density of conditions (Maps 11, 12, 13; Density of Large-, Medium- and Small Cracks, respectively) and the distance from specific locations on the ceiling (Map 14: Distance from large and Medium Cracks). These provide a visual means of analyzing cracking patterns on the ceiling.

Nearly seventy raster maps were created that represent various conditions on the ceiling deemed initially relevant for analysis. Density maps with a pixel size of 3 sq. in. were created to represent the density of all cracks, cracks by size, the intersection of same sized cracks and different sized cracks, and the displacement of cracks by the size of displacement. Distance maps were created to represent the distance from conditions like displacement and locations on the ceiling, like trusses, wall edges, and skylights. The raster maps were then scaled to a set range that represents the gradient of perceived vulnerability on the ceiling on a scale from 0 to 10. Points near existing conditions or near high densities of existing conditions were assigned a value of 10 – a high level of vulnerability. Points farthest from certain conditions or locations on the ceiling were assigned a value of 0. For example, a point on a crack was given a value of 10 as the point of highest vulnerability, and a point farthest from that crack a

value of 0. A similar assignment was made for building elements of interest, for example, the truss edge or skylight corner was assigned a value of 10. Thus, values between 0 and 10 do not always represent the same distance in inches, but represent the same gradient of vulnerability. Scaling is required because Spatial Analyst uses numerical data from the raster maps to calculate new maps. Creating a known gradient of vulnerability allows for equal comparison based on a limited scaled range between maps.

Distance-based maps are useful in combination with other maps and provide a different way of perceiving existing conditions. For example, a map based on distance from large and medium cracks is a convenient way to visualize the size and shape of panels that is otherwise difficult to read with the vector maps that only illustrate lines (Map 14: Distance from Large and Medium Cracks). The rectilinear pattern of panels in Bay 4 and 5 is clearly visible in this map. Despite the fact that many cracks in Bay 3 do not physically connect to each other, the existence of cracks within the large panel may indicate the potential for smaller panel formation based on this map.

One of the most valuable applications of ArcGIS in analyzing patterns proved to be its ability to create maps of condition density. Even relatively inexperienced ArcGIS users can easily shift from simple vector data presentation to raster analysis with the use of the density feature in Spatial Analyst. Density is a difficult feature to visualize, particularly if a condition might not be clearly

distinguishable to the naked eye, such as small crack sizes. ArcGIS provides a representation of relative concentration of conditions, allowing the user to identify anomalies or inconsistencies in the data that may lead to further queries. The results may help to interpret the particular factors responsible for a given condition that are concentrated in areas of high density, and are lacking in others.

Spatial Analyst was used to create representations of the densities of each of the crack sizes. Although the pattern on the ceiling appears consistent when viewed as a whole from below, these maps reveal that the crack sizes are not distributed evenly throughout the five bays, or throughout any individual bay. The large cracks appear to concentrate around the edges of the bays, near the walls (Map 11: Density of Large Cracks). The highest density of large cracks is found on the west side of Bay 2, just west of the area of loss. Another dense area is found along the west wall of Bay 3, close to its southern truss.

The medium cracks appear to be spread somewhat regularly throughout each bay except in Bay 5 (Map 12: Density of Medium Cracks). The highest concentration is found on the west side of Bay 5, spreading almost to the middle of the bay. The west side of Bay 4 also shows a high concentration of medium cracks, and there is a spot in the middle of Bay 1 showing a high density as well. In general, it appears that medium cracks occur throughout the entire ceiling

indicating that medium cracks may be a result of factors affecting the ceiling as a whole.

Small cracks are also evenly distributed, with several areas of high concentration toward the middle of the bays (Map 13: Density of Small Cracks). Bay 3 shows the highest concentration of small cracks, in an area between the skylights in Bays 2 and 4. Other high concentration areas include Bay 4, just east of the skylight, and Bay 1, also on the east side. The area with a high density of large cracks in Bay 2 shows the lowest density of small cracks, noticeably smaller than in any other bay.

The inconsistency in the crack size data could be explained by a number of factors. The large cracks tend to concentrate along the wall edges, which have already been identified as locations of potential movement. With either the expansion of the truss, or the continuation of the walls tilting out, a high amount of movement is expected in the areas near the walls.

Large cracks also appear concentrated on the west side of the building. Again, this could be related to the movement of the building through thermal cycling. The west side of the building will receive a higher amount of solar radiation in the summer. This thermal energy could contribute to greater movement in the trusses, resulting in larger cracks than observed on the east side. The north end of the building is expected to receive the least solar radiation,

so it would be interesting to compare the data from the south side of the ceiling to further explore the effects of solar radiation.

Small cracks are concentrated in the center of the ceiling, farthest from the walls. Distance from a known location of movement may explain why the small cracks remain small. To explore this relationship, measurements of wall tilt were taken near high densities of cracks using a plumb bob and level. The measurements showed no more than a  $\frac{1}{2}$  inch variation in a 9 foot span of the wall in three different bays, a variation that could be attributed to uneven plaster. More precise measurements are necessary to establish a relationship between wall tilt and large cracks.

Similarly, displacement showed inconsistencies that may be explained by the movement of the building. Displacement is highly concentrated along the trusses (Map 15: Density of All Displacement). Some areas in the middle of bays also show a high displacement density. It does not appear much near the walls, except in Bay 2 where a moderate amount of displacement runs along the west wall near where the ceiling and the wall meet. Bay 2 also has the largest concentration of large cracks, and the factors causing these large cracks may be contributing to displacement. Bay 1 appears to show the highest overall displacement density, with most of it concentrated in the center of the bay, particularly near the skylight and truss. The east side of the trusses between Bays 3 and 4 and Bays 4 and 5 also show high concentrations of displacement. When

this map is overlaid with the water staining condition, there appears to be a relationship between water staining and areas of high displacement density. This relationship can be further explored with the use of the raster calculator

### **5.1.3 Map Calculations**

Raster calculator is a feature of Spatial Analyst that mathematically combines the pixel values of raster maps to create new representations of the data. It is a useful way to explore relationships between conditions, and discover new insights about the vulnerability of the ceiling from the combined data - in other words, a way to visually explore interactions among variables. The first map calculations described below grew out of the known relationships between data as revealed in the previous quantification analysis and the creation of the raster maps. Then, maps were created to test the two hypotheses about crack formation to compare the results. Finally, the hypothesis maps were combined to create a new map that represents both scenarios.

Based on the conditions quantification analysis described above, there appears to be a relationship between large cracks and displacement, and large cracks and water staining. Most large cracks have some displacement along their length, and a higher percentage of large cracks occur in areas of water staining. Large cracks have more opportunity to displace as they are wider, and may continue to grow if already displaced, leading to detachment and/or loss. Water staining indicates exposure to water, and thus a potential for weakening the

plaster. The combination of weakened plaster and large cracks could further damage the ceiling.

Raster density maps also show that displacement is related to water staining, particularly near the skylights. Because displacement is determined to be an indicator of detachment and thus the potential for loss, it is a significant consideration. Since displacement varied in size, ranging from over 20 mm to less than 1 mm, a base map of displacement was created that weighted it incrementally, with the larger displacement values weighted heavier than the smaller on a scale of 1 to 7. In this case, distance was mapped, since the relative location of displacement is the important factor. The maps were combined to create a base map of displacement values for use in the later analysis. This map was also scaled 0-10 for use by raster calculator. (Map 16: Displacement Base Map)

The map created from combining the displacement base map with distance from water staining (Map 17: Distance from Displacement and Water Staining) illustrates how the two variables show a relationship near the skylight in Bay 2 and near the water staining in Bay 4 (darker areas correspond to poorer conditions or locations). Combining the density of large cracks to the displacement map reveal that the two variables correspond near the east side of Bay 4 in an area of water staining (Map 18: Density of Large Cracks and Distance from Displacement) and also along the west edges of Bays 2 and 3. The result is a



map that shows a high level of vulnerability on the west side of Bays 2 and 3 where the large cracks are concentrated as well as the east side of Bays 2 and 4. Adding distance from water staining to these maps shows a correspondence among the three variables in both Bays 2 and 4, as well as Bay 1 near the roof hatch. (Map 19: Density of Large Cracks and Distance from Displacement and Water Staining). The area of high vulnerability near the roof hatch is also close to another area of loss which has since been repaired. This map also shows high levels of vulnerability in Bays 2 and 4, approximate to the large area of water staining and the large cracks. There also appears to be high vulnerability near the north ends of the skylight in Bay 2. The relationship among these three maps suggests that these variables should be further investigated as predictors of vulnerability.

Maps were then created to simulate the two approaches to the cracking pattern: - as a cause or a symptom of detachment. The two different approaches yielded slightly different maps as they are dependant on different factors. Both sets, however, correlated with the existing conditions noted from the roof probes as well as the areas that were defined as “detached” in the conditions assessment, although not used in the raster analysis.

The first set of maps assumes cracking causes detachment. If this were the case, the framing of the ceiling would have a large impact on the location of vulnerability to detachment. Distance from the various structural supports like

nailers, wall edges, and trusses were used in this map analysis. Similarly, the large and medium cracks would be of concern if the cracks themselves lead to detachment. Thus, the densities of large and medium cracks were included in the analysis along with the displacement map. An example of a map created using these variables can be found in Map 20: Cause Map. Areas of vulnerability in Map 20 tend to concentrate along the trusses, and in Bays 2 and 4. The area in Bay 4 corresponds to the area of water staining, even though water staining was not used as a variable. This map, however, does not support the argument based on the known loss. The area of loss and the probe area opposite the loss do not exhibit high vulnerability on this map. This may suggest that the loss from 2003 was an anomaly or a result of other factors, like water damage, which was not used as a variable here.

To test the accuracy of this map, it was compared with the existing conditions gathered as part of the conditions assessment phase. While detachment was not used as a condition for analysis, some detachment was recorded in the field. The areas of perceived detachment through the tap test generally fall into places on the map where the GIS indicated a higher risk for detachment. Likewise, the results of these maps correlate to the conditions observed with most of the roof probes. However, the area of loss and the probe opposite the area of loss do not exhibit high vulnerability with this map.

Exploration of different variables may be necessary to create a more accurate map of vulnerability.

The map created to simulate cracking as a symptom of detachment showed correspondence with the area of recent loss (Map 21: Symptom Map). The variables used in the creation of this map included distance maps related to displacement, the trusses, the nailers, the areas of water staining and the cracks located within those areas, and the skylights and skylight corners. This map illustrates areas of concern generally along the trusses and near locations of water staining. The areas deemed least vulnerable include the northwest corner of the building as well as the west side of Bays 4 and 5. Little water damage was noted in these areas. The areas of highest vulnerability suggested in the maps correspond to known areas of damage found through the roof probes.

The two maps share high concentrations of vulnerability near the skylights and along the truss in Bay 4, as well as near the north end of the skylight in Bay 2. Both show low levels of vulnerability along the north edge of the ceiling and the corners of bay 5. These areas are both fairly distant from areas of water staining, despite the fact that water staining was only used as a variable in the symptom map. However, the cause map does not highlight vulnerability in the center of Bay 3, which is much darker in the symptom map.

A combination of these two types of maps creates an even clearer picture of the potential threat to the ceiling and correlates well to the known conditions

(Map 22: Combination Map). It shows the areas of potential threat to be highest in Bays 2 and 4, which are both bays with significant water staining and concentration of large cracks. Vulnerability is also concentrated along the trusses. The area of loss is included near the high threat area despite the fact that loss was not a variable in creating the maps. Similarly, the locations where the probes revealed sound plaster are relatively low in threat, while areas deemed unsound are high in threat. An area that was not probed but may be of concern based on this map is the east side of Bay 2. Bay 5 appears to be in the best condition, with relatively low vulnerability along the west side. Bay 1 shows greatest vulnerability in the center, near the truss. This is not surprising given its proximity to one of the worst areas as revealed by the probes as well as the area of recent loss. This final map accounts for the multiple variables deemed important to the instability of the ceiling and perhaps signifies the best representation of the potential threat to the ceiling. The existence of darker areas along trusses, near water staining, and in proximity to concentrations of large cracks, as well the correspondence to known conditions through probes, confirm the potential use of this map as a guide of vulnerability.

Given the large number of variables considered for any type of diagnostic methodology, a clear understanding of the significant variables for the given situation is vital. Raster calculator has the ability to combine large sets of data, and an endless number of maps can be created from these variables, many of

which may not reveal much about the state of the building. Moreover, not all variables are necessarily known. The user, therefore, must be careful about sacrificing clarity to include all of the known variables, and make educated decisions about what to use and how. The key is to identify potentially significant variables based on previous observation and research to develop these maps. Ultimately, the goal is to create representations of the combinations of the perceived factors affecting the ceiling to aid in future monitoring and treatment.

There are limitations affecting the results of this analysis. While the five bays surveyed were determined to be representative of the entire ceiling, not having the entire space available may influence the raster analysis. Because raster maps create a continuous surface, variables that span bays will not be represented fully. This may explain why Bay 5 showed limited vulnerability on its south end. Variables in Bay 6 that span into Bay 5 and affect ceiling performance, like water staining or distance from skylights, are not represented in this analysis. Similarly, it is difficult to compare crack size and direction of the various bays in relation to their location since there is limited data for comparison. For example, if the entire building is racking, diagonal cracking would be expected in Bay 9 as well as Bay 1. These questions should be addressed after completing an assessment of the remaining four bays. A monitoring program is scheduled to begin in the summer of 2008.

## 7.0 Nondestructive Testing

Early in the research process, we sought to supplement and substantiate the GIS results with other nondestructive testing (NDT) techniques. A literature review was conducted on common techniques used to locate faults like voids, detachment, and delamination of materials. However, most studies were conducted only on plaster systems attached to masonry and none were examined for use in wood-frame systems. As no case studies were found that appeared applicable for wood-framed plaster systems, NDT will not be conducted on the Wagner ceiling until further research is completed.

Common NDT techniques include acoustic methods like laser vibrometry<sup>73,74,75</sup> and air-coupled ultrasound, and thermal methods like infrared thermography (IRT).<sup>76,77</sup> IRT, which relies on the temperature variations in

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<sup>73</sup> P. Castellini, Enrico Esposito, V. Legoux, N. Paone, M. Stefanaggi, and E.P. Tomasini. "On field validation of non-invasive laser scanning vibrometer measurement of damaged frescoes: experiments on large walls artificially aged." *Journal of Cultural Heritage* 1, supplement 1(2000): S349-S356.

<sup>74</sup> Paolo Castellini, Enrico Esposito, Barbara Marchetti, Nicola Paone, and Erinco P. Tomasini. "New Applications of Scanning Laser Vibrometry (SLDV) to non-destructive diagnostics of artworks: mosaics, ceramics, inlaid wood and easel painting." *Journal of Cultural Heritage* 4 (2003): 321-329.

<sup>75</sup> Joseph Vignola, Joseph A. Bucaro, Brian R. Lemon, George W. Adamas, Andrew J. Kurdila, Barbara Marchetti, Enrico Esposito, Enrico Tomasini, Harry Simpson, and Brian H. Houston. "Locating Faults in Wall Paintings at the U.S. Capitol by Shaker-Based Laser Vibrometry." *APT Bulletin* 36, no. 1 (2005): 25-33.

<sup>76</sup> G. Schirripa Spagnolo, G. Guattari, E. Grinzato, P.G. Bison, D. Paoletti, and D. Ambrosini. "Frescoes diagnostics by electro-optic holography and infrared thermography." In *Proceeding of the 6th International Conference on "Non-Destructive Testing and Microanalysis for the Diagnostics and Conservation of the Cultural and Environmental Heritage": Rome, May 17th-20th 1999*. Edited by Maurizio Marabelli, and Concetto Parisi. (Italian Society for Nondestructive Testing, 1999).

<sup>77</sup> N. P. Avdelidis, and A. Moropoulou. "Applications of infrared thermography for the investigation of historic structures." *Journal of Cultural Heritage* 5, (2004): 119-127.

materials, has successfully been used to identify structural elements, moisture infiltration and thermal bridges in wood-framed buildings.<sup>78</sup> The passive approach, in which no artificial heat source is applied, was deemed useful for detecting anomalies in walls or ceilings.<sup>79</sup> An active approach, where readings are taken after an artificial heat source has been applied, could also provide accurate results, but is more time consuming and expensive. It is not clear if one might use this method on a wood-framed plaster system to identify faults between the plaster and the wood. Because of the thermal inconsistency of the ceiling-to-roof opening at the Wagner, IRT may not be practical, particularly if an active approach must be used to generate readable imaging. However, it is a potential method of testing that could be explored.

Scanning Laser Vibrometry is a promising technique for the Wagner ceiling. It has been used on several plaster investigations on masonry, but has not been documented on wood-framed systems. The technique works by exciting surfaces and recording the frequencies of the materials to identify anomalies in the material through a variation in vibration response.<sup>80</sup> A void or detachment is assumed to have a different vibration response from sound plaster, thus indicating areas of concern.

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<sup>78</sup> Elisabeth Rosina and Elwin C. Robison, "Applying Infrared Thermography to Historic Wood-framed Buildings in North America." *APT Bulletin* 33, no. 4 (2002): 37-44.

<sup>79</sup> *Ibid.*

<sup>80</sup> P.L. Swanson and J. Rettkowski, "Damage Delineation in Structures Using Laser Vibrometry and Remote Excitation." In *Proceedings of the 2004 SEM X International Congress and Exposition on*



**Figure 17: Plaster mock-up “B” – simulating detachment between the lath and the scratch coat.**

To test the potential for extending this methodology to wood-frame systems, a study was undertaken in conjunction with the Applied Research Laboratory at the Pennsylvania State University in State College, Pennsylvania. In this study, three ceiling mock-ups were designed to closely reproduce the condition of most concern at the Wagner – detachment. Frames of approximately two feet square were built to hold the plaster. Wood lath of similar dimensions were attached to the frame with the same sized gaps as found at the Wagner. Since lime (the original binder of the plaster) could not be used because of its long set time, a proxy material called Structo-Lite, a pre-mixed, perlite-aggregate gypsum, was



substituted. Voids in the plaster were created using plexiglass strips of different thicknesses. The strips were placed either directly on the lath and plastered over to imitate detachment between plaster and lath, or in between plaster layers to imitate detachment within the plaster. Upon drying, the strips were removed, leaving voids of varying widths throughout the mock-up. One mock-up was plastered normally as a control to which the other two mock-ups could be compared.

Testing was performed at the Applied Research Laboratory using a Scanning Laser Doppler Vibrometer (SLDV).<sup>81</sup> (Full report in Appendix B) The surfaces of the plaster mock-ups were excited in two ways - with a speaker and with a shaker system - to determine the most effective method. The SLDV measured the velocity fluctuations of the plaster surface with each method to develop a frequency response function, which could be compared to the control.

The results of the testing were inconclusive since no clear voids could be located in either of the mock-ups. Several recommendations were presented for further research. These recommendations include using a different excitation source at a higher frequency to increase the response of the surface, or developing a method that can compare the local properties of a sample to their global properties to account for the difference physical properties between the

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<sup>81</sup> Jesse Zoll, Steve Young and Dean Capone. "The Use of Scanning Laser Dopple Vibrometry for Non-destructive evaluation of Structural Flaws in Plaster." (Applied Research Laboratory, The Pennsylvania State University, April 2008.)

samples. Local properties will also be of concern if used on the Wagner ceiling as the plaster is not a uniform material and may differ throughout the space. Further research is planned for the fall of 2008.

The lack of viable non-destructive testing options for plaster on lath systems highlights the value of a methodology using GIS. It is both non-destructive and relatively inexpensive to operate compared to most NDT techniques, particularly with an experienced user. While the results of the GIS analysis in this case cannot be confirmed through NDT, the validity of the methodology has been established as a way to enhance the diagnostic process in the absence of viable alternatives.

## 8.0 Conclusion

As a supplement to the diagnostic process, GIS provides several unique capabilities to enhance our understanding of building deterioration. It allows:

- quantifying data to establish relationships and help support conclusions
- isolating conditions and combining those conditions in new ways to reveal potential interactions among variables

- visualizing aspects of data otherwise difficult to observe

- exploring and synthesizing hypotheses about building problems

- presenting complex interactions in a clear and easy to understand format

- enhancing results with statistical methods of analysis like regression

Attempts to use nondestructive testing methods to detect voids in wood-frame plaster systems proved unsuccessful, demonstrating the value of a tool like GIS for analysis of this type.

GIS also has limitations which should be recognized before embarking on any analysis. While GIS is a useful tool in allowing conservators to view conditions in new ways, the learning curve for running the software is quite steep and a significant amount of training time is required before one understands its subtleties. For situations where there are many conditions to correlate, the time investment in a GIS analysis may prove fruitful. However, if only a few conditions are available for comparison, GIS may not be the most efficient method of investigation. Finally, the GIS analysis is determined using

conditions collected at a single point in time. Coupling the GIS analysis with an understanding of how these conditions have changed over time (periodic monitoring), will significantly enhance our ability to understand real cause and effect relationships.

A very useful, potential benefit of GIS is its ability to process conditions into data that can be analyzed by statistical methods, such as regression. Although regression analysis is a valuable way to approach predictive modeling, it is also a highly sophisticated tool that requires expert knowledge to fully understand how to interpret the results. Initial regression analysis on the GIS data did not produce meaningful and useful information and was therefore eliminated from this thesis. Expert advice is required when analyzing GIS data using advanced analytical methodology. The complexity of this type of analysis may require aid from a statistician, further reducing the widespread applicability of the process. As GIS becomes more widely used by conservators, training in the software and advanced statistical methods may become part of the mainstream learning experience.

Most importantly, it is vital to understand that GIS is just one tool for diagnosis. By itself, it will not provide all of the answers – it must be coupled with results from other diagnostic methods to fully inform the problem solving process.

The GIS analysis of the Exhibit Hall ceiling reinforced several key ideas about the vulnerability of the Wagner ceiling. While many of these conclusions were drawn after the initial assessment, the raster map analysis confirmed early hypotheses and created quantifiable data and visual representations.

1. Water staining in conjunction with cracking and displacement is a primary threat to the integrity of the plaster.

2. There is a clear relationship between large cracks and displacement, highlighting the need for future monitoring of these cracks.

3. Large displacement (over 5 mm) is largely found along the truss edges. Displacement throughout the bays is widespread, but small (less than 3 mm).

4. The nailers, though they appear related to the cracking, do not seem to be high areas of threat unless they correlate with other damaging conditions.

5. The skylights have leaked over time, making the surrounding plaster areas vulnerable. Continued leaking will exacerbate the already existing problem.

6. Displacement and separation along the truss is a significant source of vulnerability. The lack of key formation below the nailers, the extra plaster thickness and the on-going and variable movement of the truss renders the plaster at risk for damage. Truss separations near the skylights – known areas of water infiltration – are even more vulnerable.

Evidence of these conclusions can be seen in the series of maps in Appendix A. The GIS maps enhance the understanding of the analysis and provide a base for comparison with future assessments.

Assessment of the remaining four bays and monitoring of the building for structural movement, environmental conditions, and crack formation and growth will considerably improve our understanding of areas of potential vulnerability. This data combined with a full GIS analysis of the entire ceiling and subsequent regression analysis will provide enhanced visual maps of the areas of vulnerability that can provide a guide for investigation of treatment options and lead to better informed decisions.

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## Appendix A: Maps

### *Vector Maps*

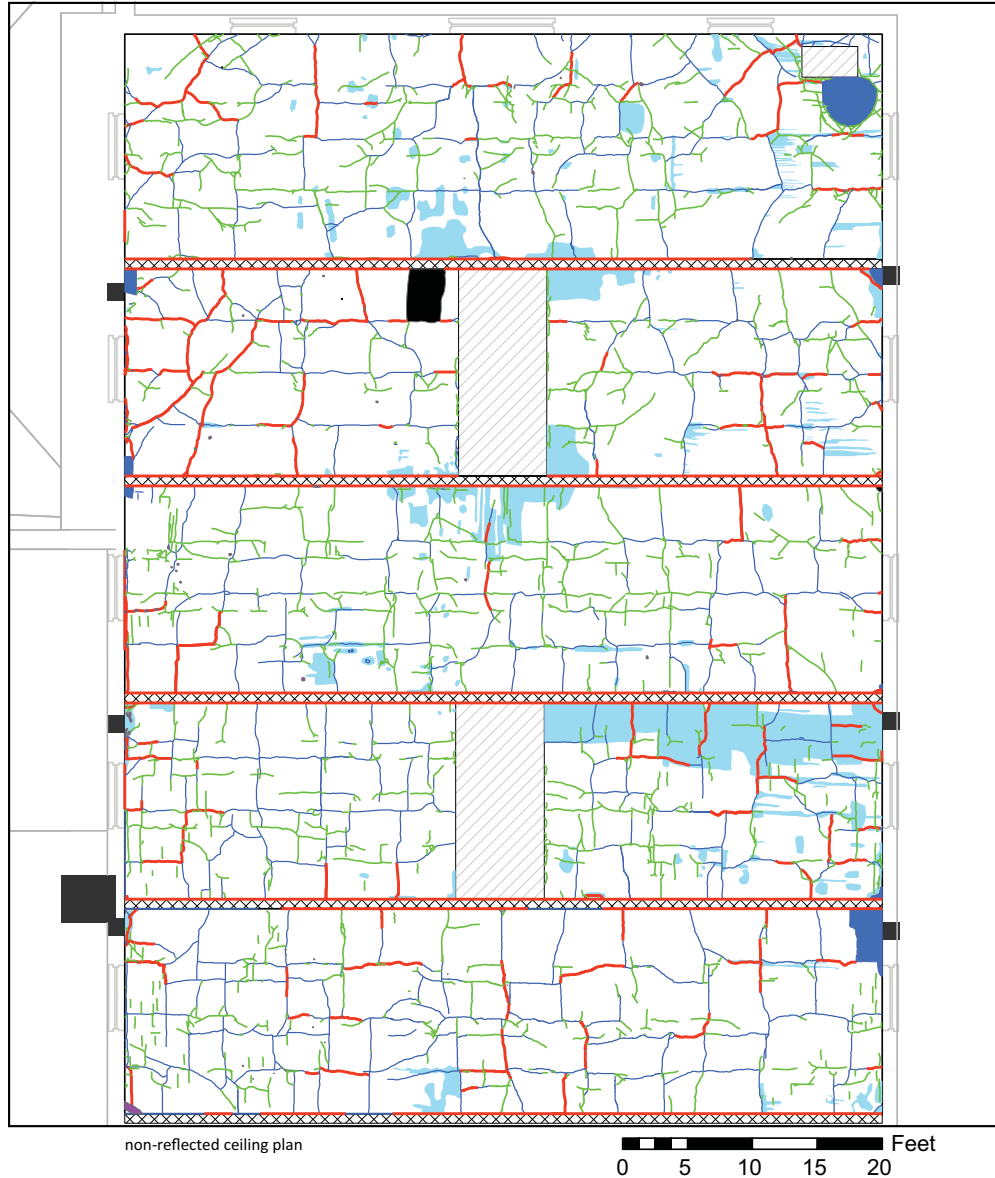
Map 1: All conditions, no displacement.....	115
Map 2: All conditions, with displacement	
Map 3: Probe locations	
Map 4: Cracks by Bay	
Map 5: Crack Distribution by Bay	
Map 6: Displacement	
Map 7: Water Staining	
Map 8: All Conditions, with nailers	
Map 9: Panel size determined by Large and Medium cracks	
Map 10: Panel size determined by all cracks	

### *Raster Maps*

Map11: Density of Large Cracks	
Map 12: Density of Medium Cracks	
Map 13: Density of Small Cracks	
Map 14: Distance from Medium and Large cracks	
Map 15: Density of all displacement	
Map 16: Displacement base Map	
Map 17: Distance from Density and Displacement	
Map 18: Density of Large Cracks and Distance from Displacement	
Map19: Density of Large cracks and Distance from Water Staining and Displacement	
Map 20: Cause Map	
Map 21: Symptom Map	
Map 22: Combination Map	

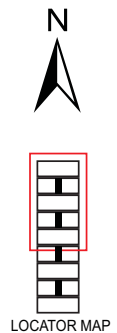
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 GIS ASSESSMENT AND ANALYSIS

Map 1: All Conditions, without displacement



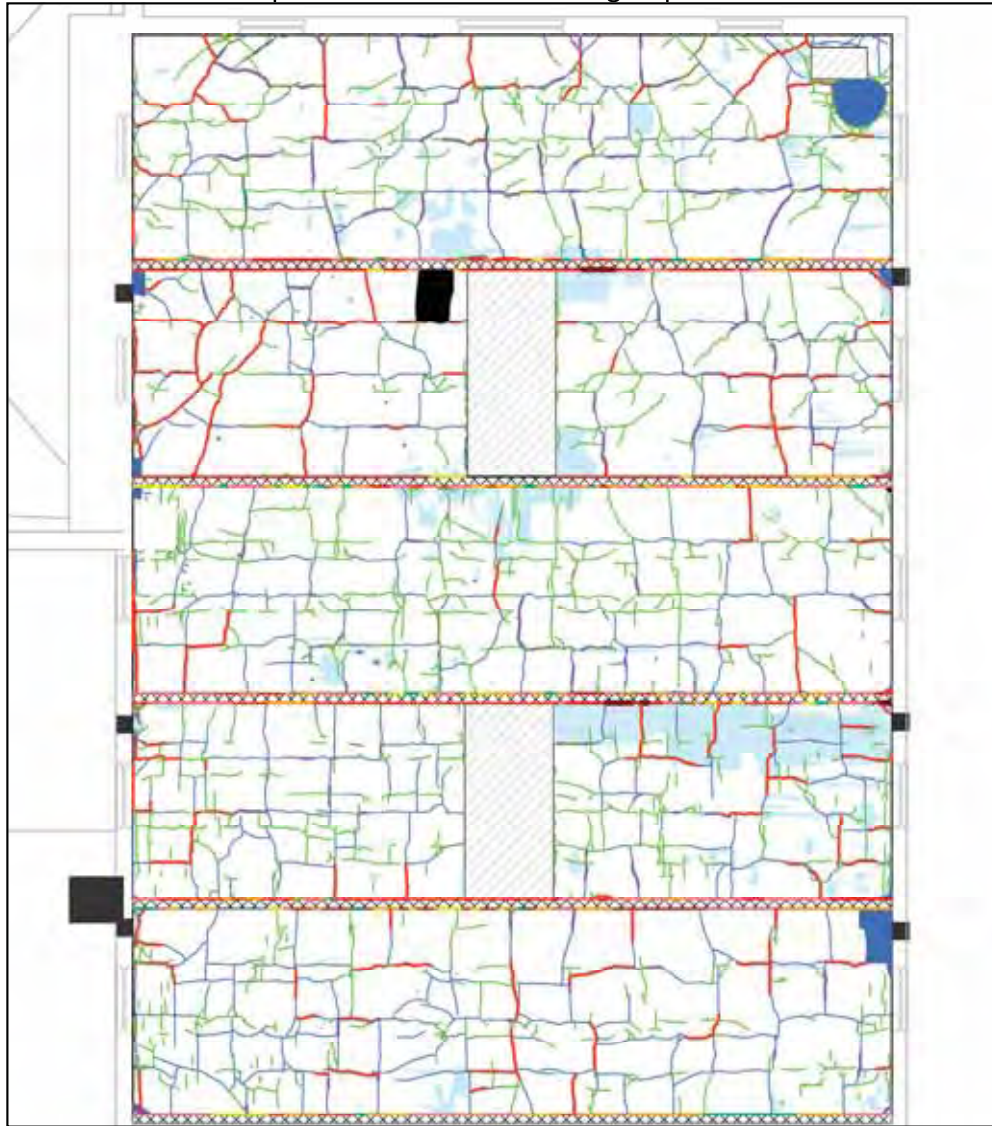
**LEGEND**

- |               |                 |                      |
|---------------|-----------------|----------------------|
| Large Cracks  | Previous Repair | Total Loss           |
| Medium Cracks | Water Staining  | Surface Accretion    |
| Small Cracks  | Partial Loss    |                      |
| Walls/Windows | Chimney         | Skylights/Roof Hatch |
|               |                 | Truss                |





Map 2: All Conditions including displacement



non-reflected ceiling plan

0 5 10 15 20 Feet

**LEGEND**

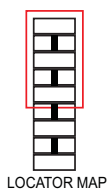
Displacement

- > 20 mm
- 10 < 20 mm
- 5 < 10 mm
- 3 < 5 mm
- 2 < 3 mm
- 1 < 2 mm
- < 1 mm

- Large Cracks
- Medium Cracks
- Small Cracks

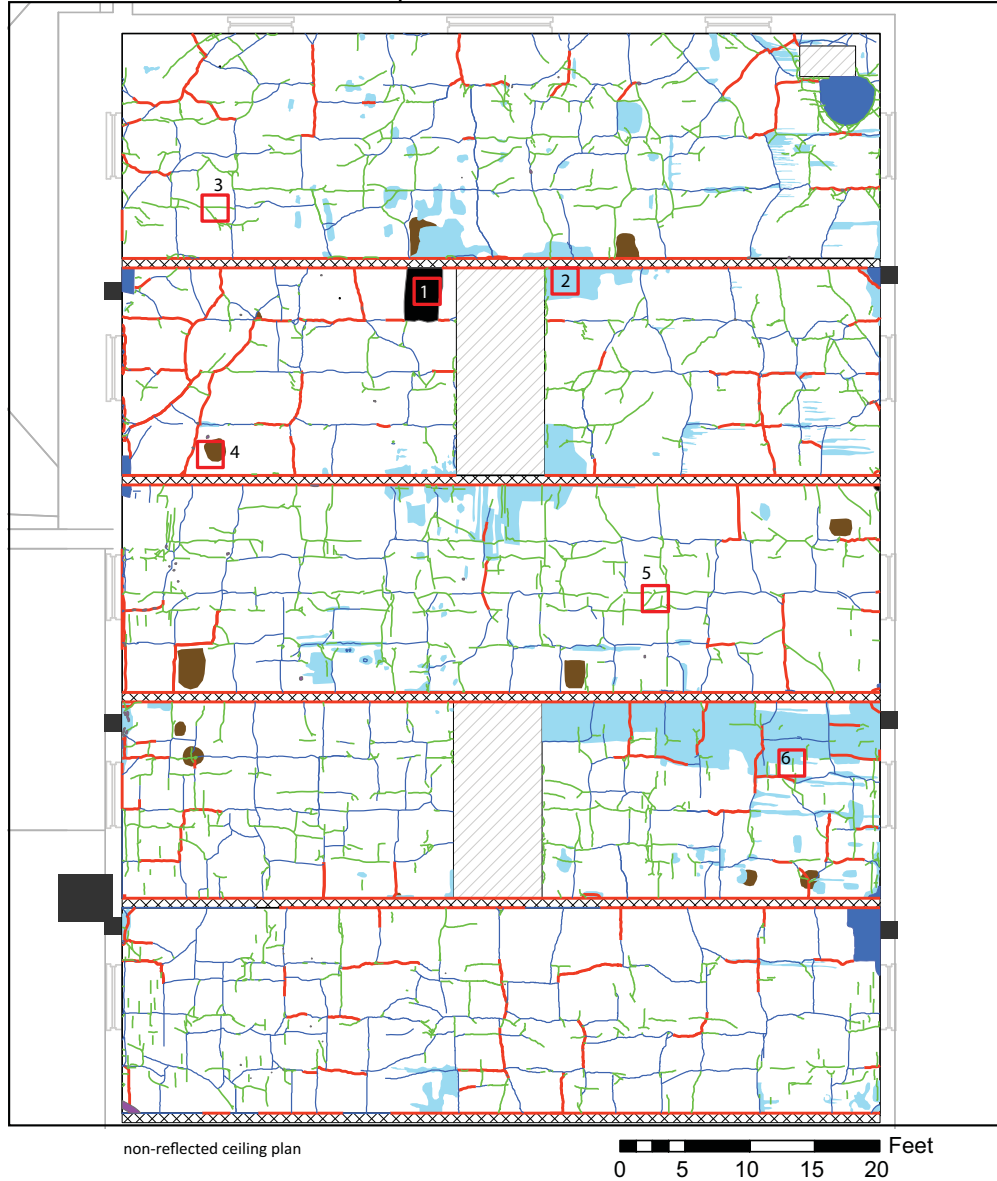
- Previous Repair
- Water Staining
- Partial Loss
- Total Loss
- Surface Accretion

- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



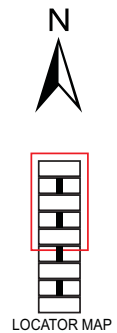
LOCATOR MAP

Map 3: Probe Locations

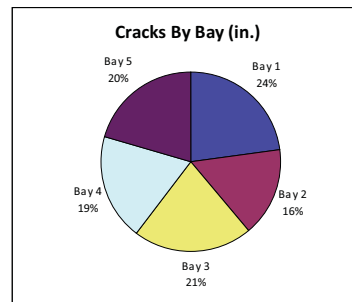
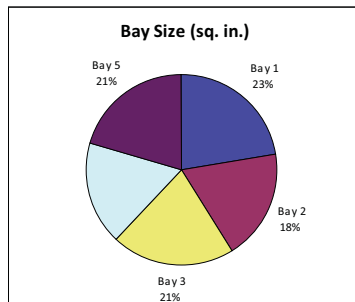
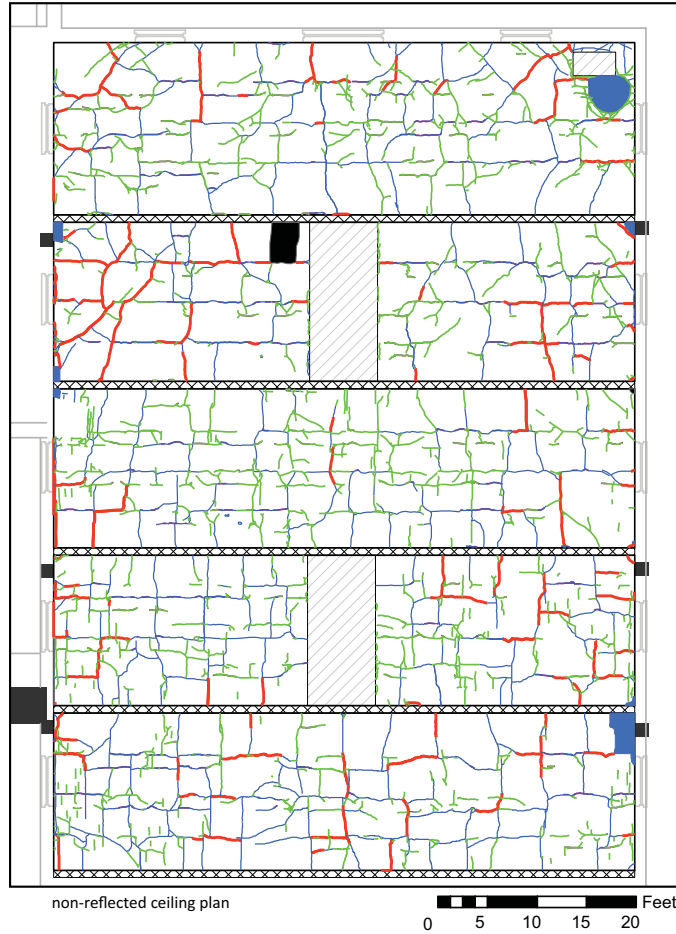


**LEGEND**

- |               |                 |  |
|---------------|-----------------|--|
| Probes        | Previous Repair | Total Loss                                   |
| Large Cracks  | Water Staining  | Surface Accretion                            |
| Medium Cracks | Partial Loss    | Detachment (percieved through sounding only) |
| Small Cracks  |                 |  |
| Walls/Windows | Chimney         | Skylights/Roof Hatch                         |
|               |                 | Truss  |

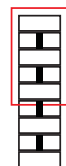


Map 4: Cracks By Bay



**LEGEND**

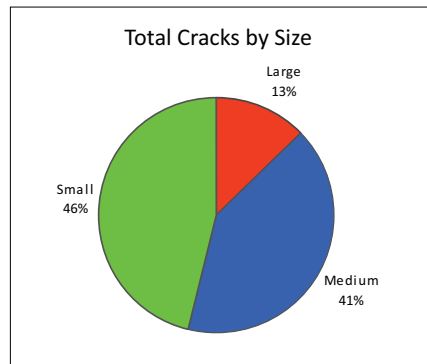
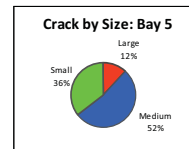
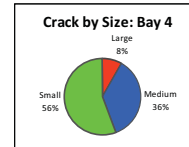
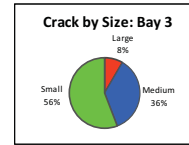
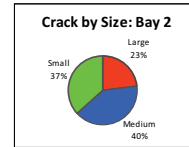
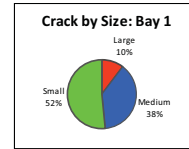
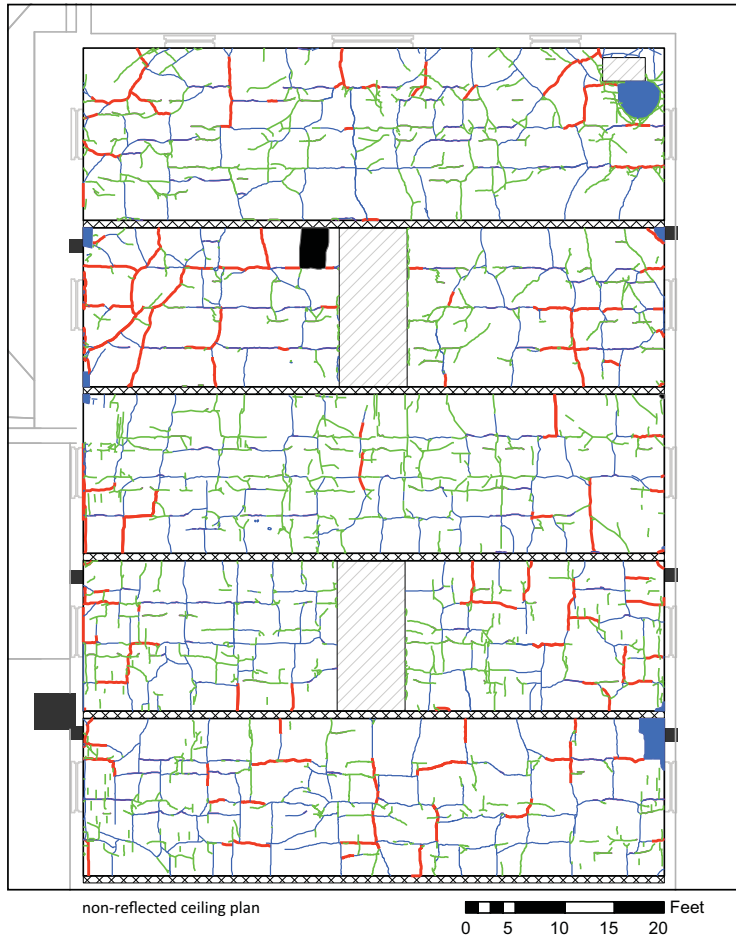
- Large Cracks
- Medium Cracks
- Small Cracks
- Previous Repair
- Total Loss
- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



LOCATOR MAP

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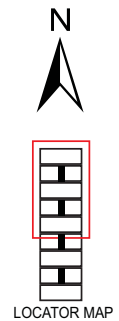
Map 5: Crack Distribution by Bay



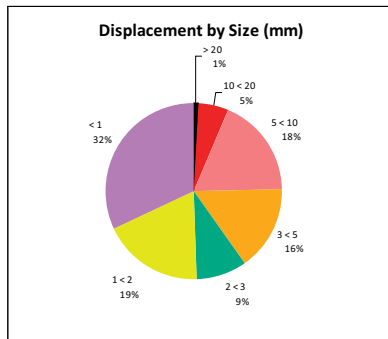
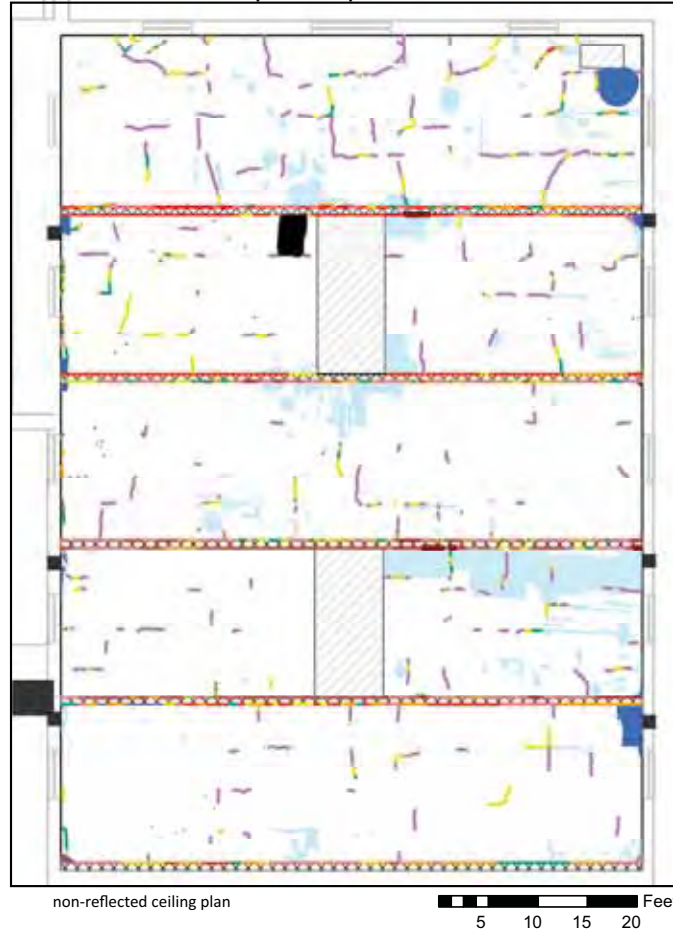
**LEGEND**

- Large Cracks
- Medium Cracks
- Small Cracks
- Previous Repair
- Total Loss

- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



Map 6: Displacement



**LEGEND**

Displacement

- > 20 mm
- 10 < 20 mm
- 5 < 10 mm
- 3 < 5 mm
- 2 < 3 mm
- 1 < 2 mm
- < 1 mm

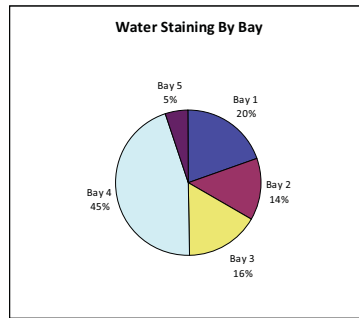
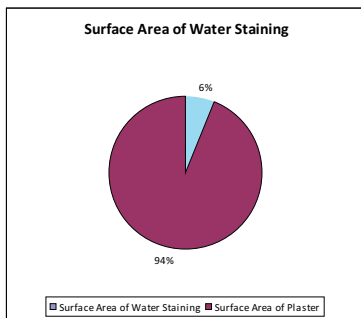
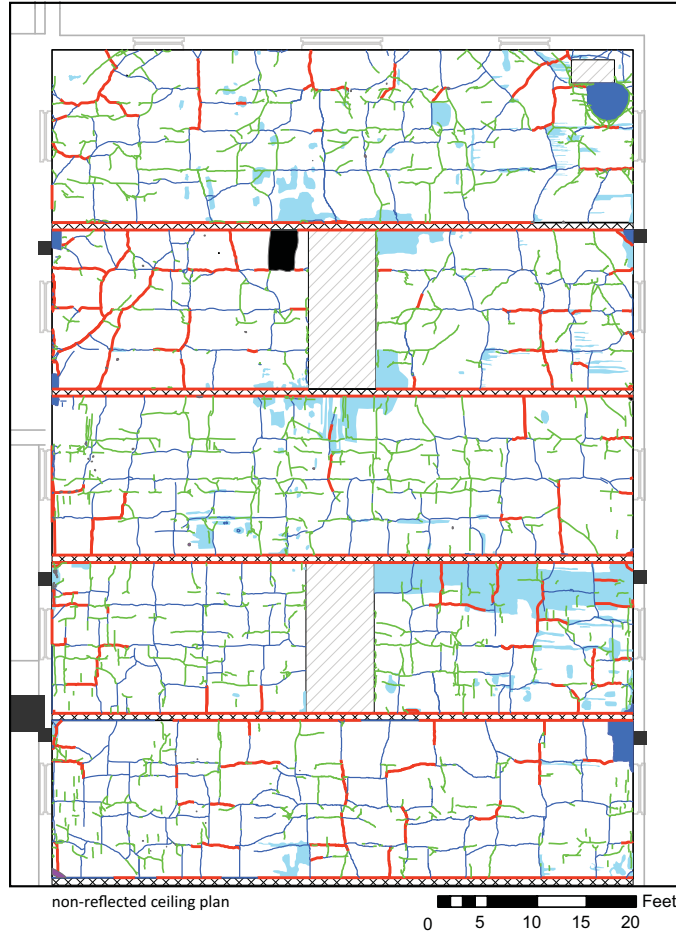
- Previous Repair
- Water Staining
- Partial Loss
- Total Loss
- Surface Accretion

- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



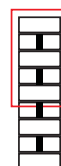
LOCATOR MAP

Map 7: Water Staining



**LEGEND**

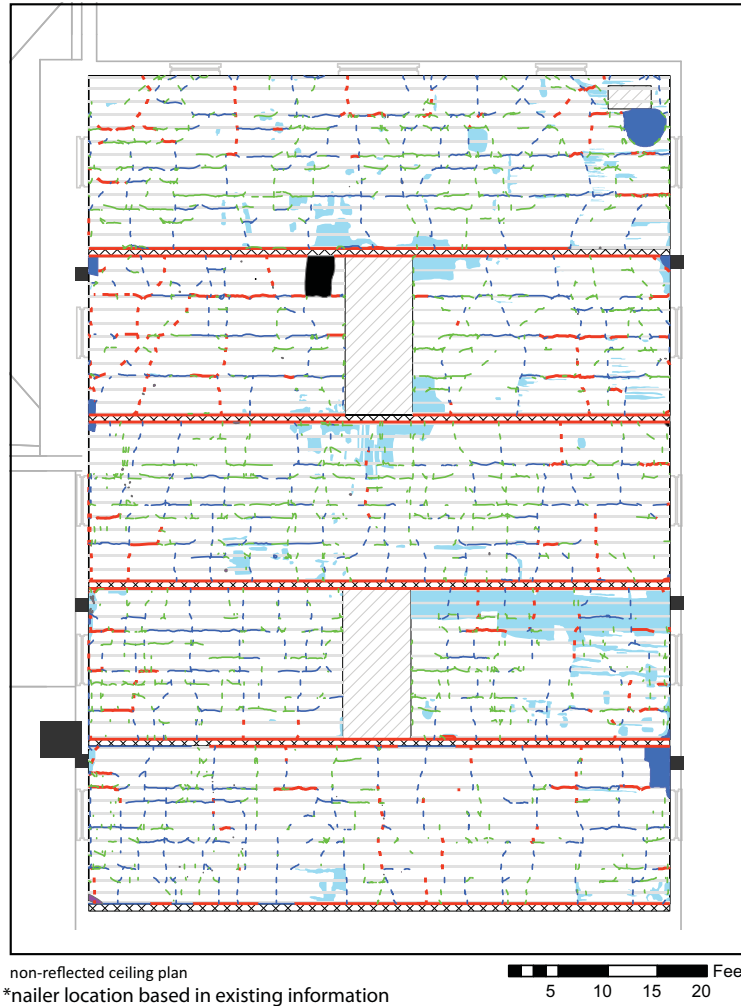
- Large Cracks
- Medium Cracks
- Small Cracks
- Water Staining
- Previous Repair
- Total Loss
- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



LOCATOR MAP

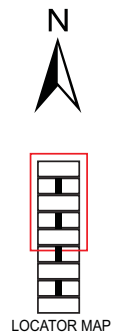
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Map 8: Cracks within 1 1/2 inches of Nailers



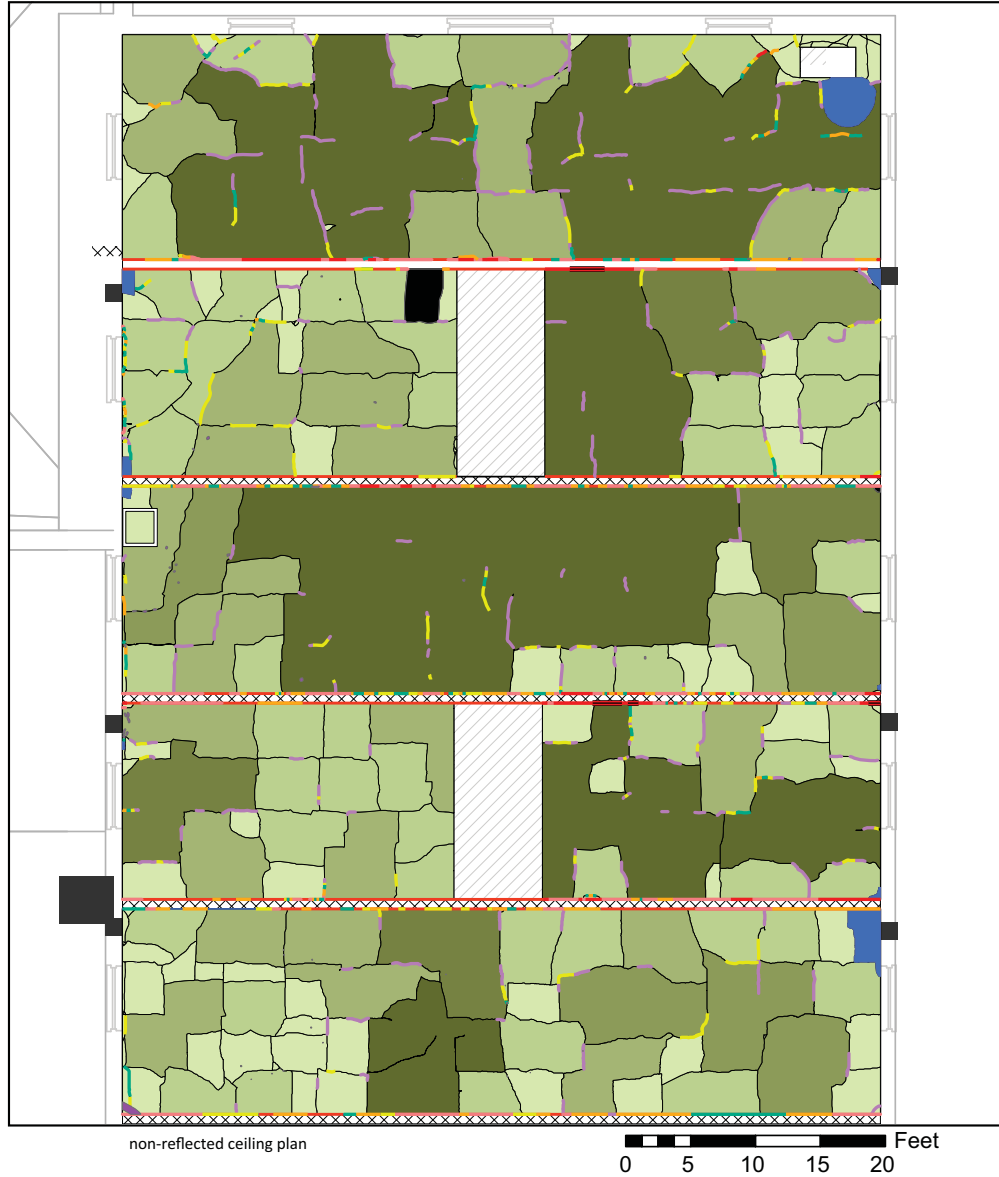
**LEGEND**

- |                 |                   |                        |
|-----------------|-------------------|------------------------|
| — Large Cracks  | ■ Previous Repair | ■ Total Loss           |
| — Medium Cracks | ■ Water Staining  | ■ Surface Accretion    |
| — Small Cracks  | ■ Partial Loss    | ■ Nailers              |
| — Walls/Windows | ■ Chimney         | ■ Skylights/Roof Hatch |
|                 |                   | ■ Truss                |



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Map 9: Panel Size (defined by Large and Medium Cracks)



**LEGEND**

Panel Size (sq. in.)

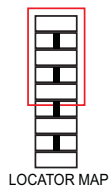
- 0 - 2,000
- 2,000.01 - 4,000
- 4,000.01 - 6,000
- 6,000.01 - 8,000
- 8,000.01 - 10,000
- over 10,000

Displacement

- > 20 mm
- 10 < 20 mm
- 5 < 10 mm
- 3 < 5 mm
- 2 < 3 mm
- 1 < 2 mm
- < 1 mm

- Previous Repair
- Partial Loss
- Total Loss

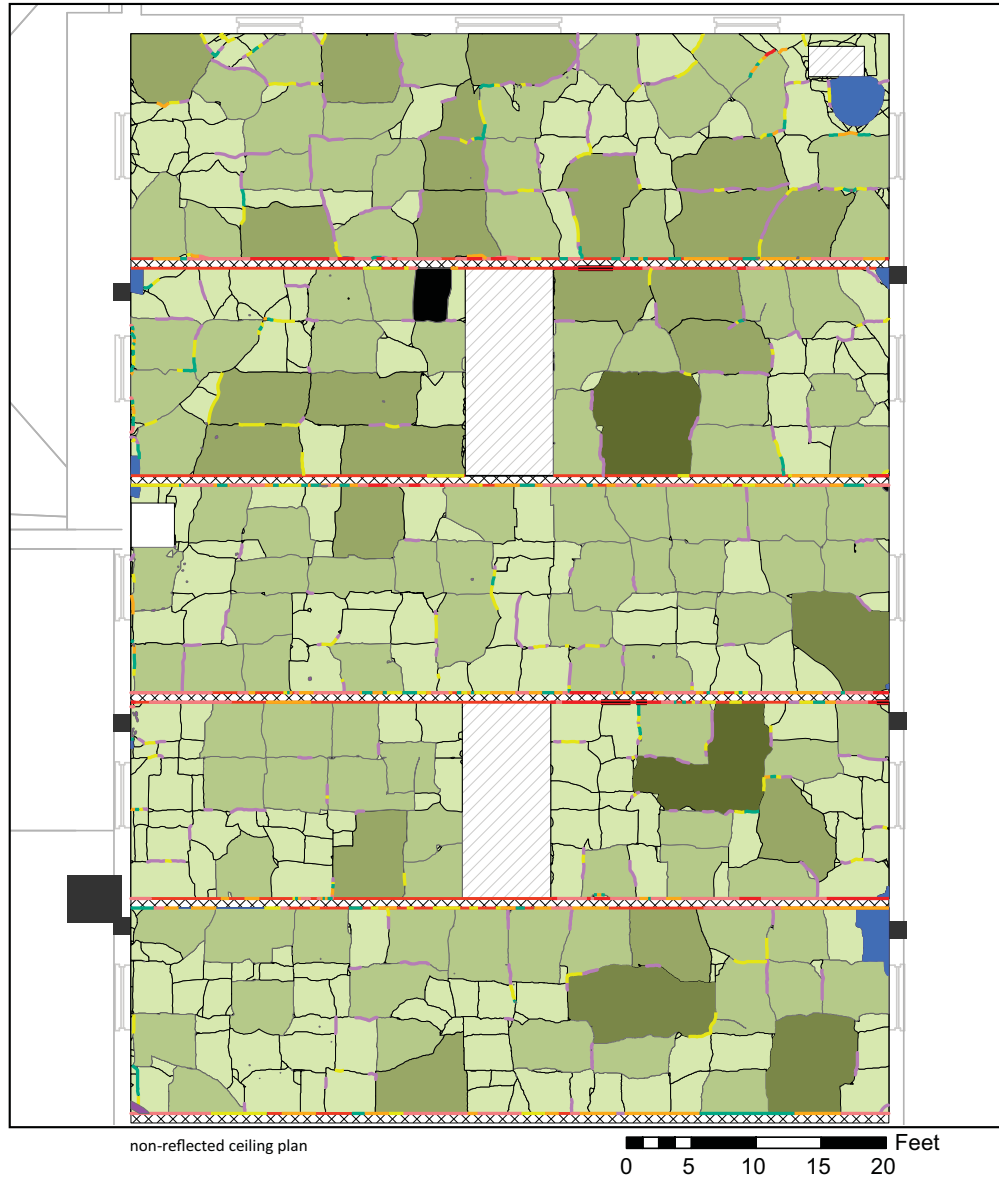
- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss





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GIS ASSESSMENT AND ANALYSIS

Map 10: Panel Size (defined by All Cracks)



**LEGEND**

Panel Size (sq. in.)

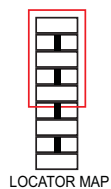
- 0 - 2,000
- 2,000.01 - 4,000
- 4,000.01 - 6,000
- 6,000.01 - 8,000
- over 8,000

Displacement

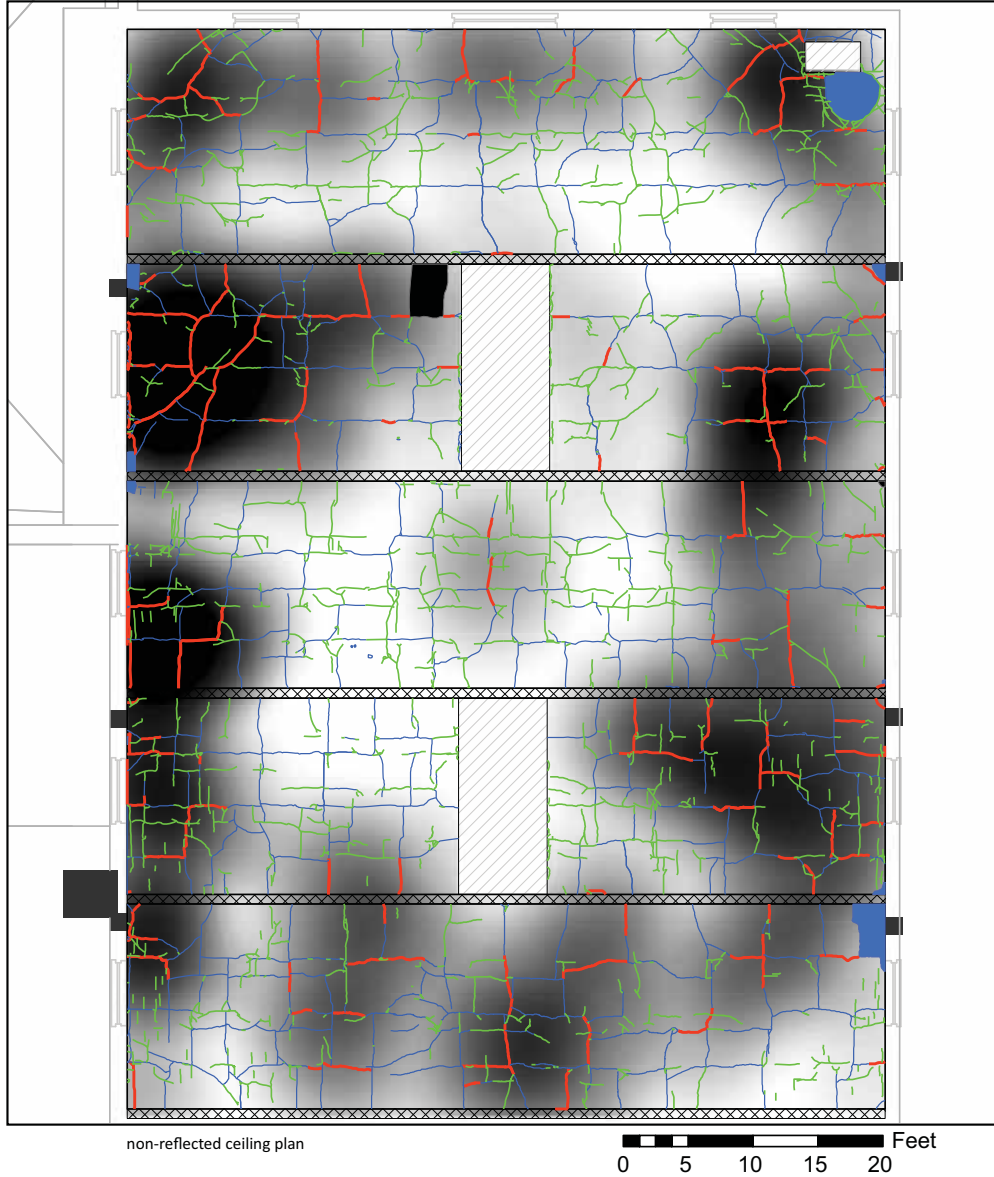
- > 20 mm
- 10 < 20 mm
- 5 < 10 mm
- 3 < 5 mm
- 2 < 3 mm
- 1 < 2 mm
- < 1 mm

- Previous Repair
- Partial Loss
- Total Loss

- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



Map 11: Density of Large Cracks\*



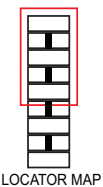
**LEGEND**



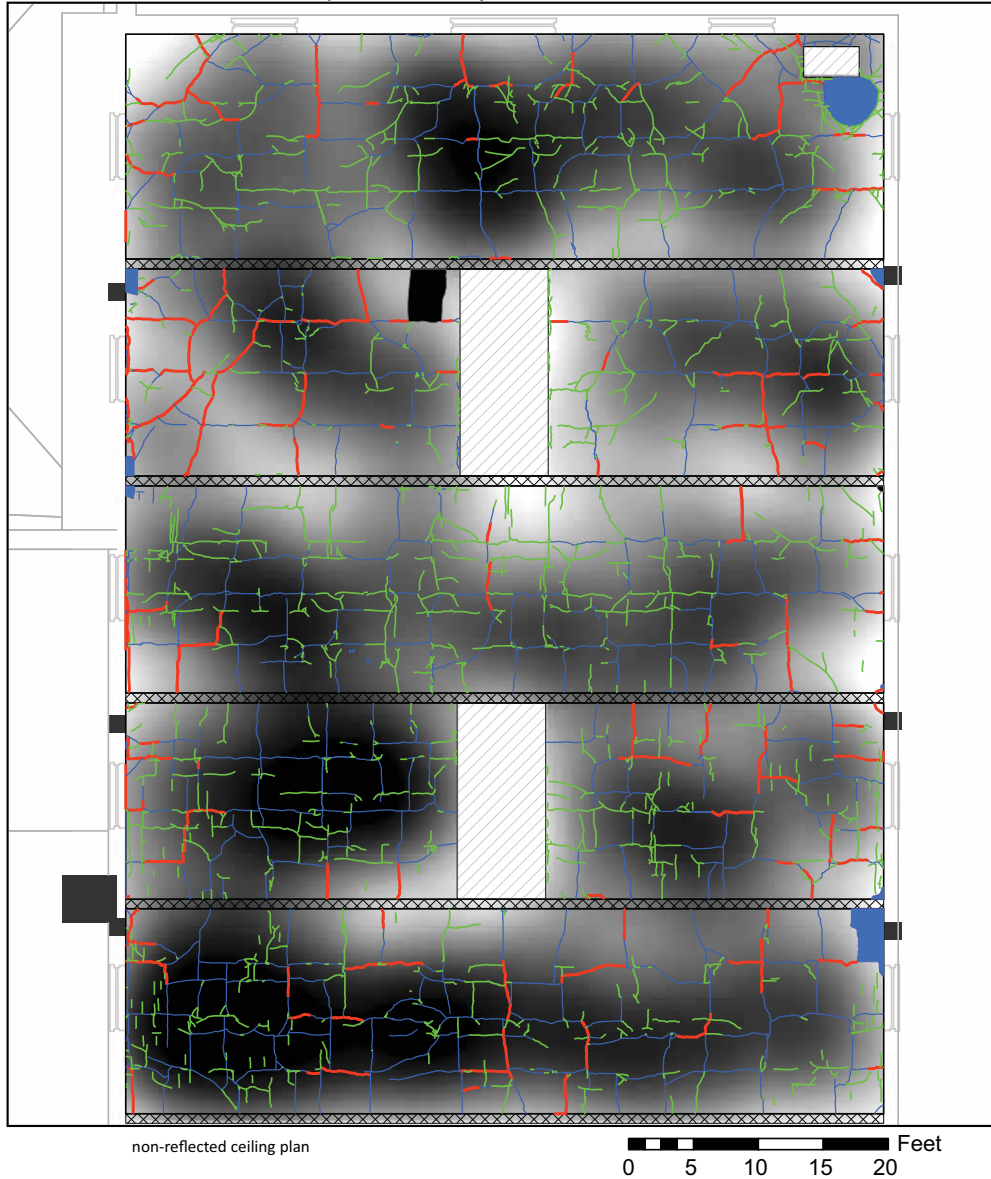
- Large Cracks
- Medium Cracks
- Small Cracks
- Previous Repair
- Total Loss

\*does not include separations along the truss

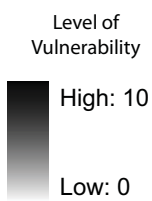
- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



Map 12: Density of Medium Cracks\*



**LEGEND**

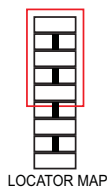


- Large Cracks
- Medium Cracks
- Small Cracks

- Previous Repair
- Total Loss

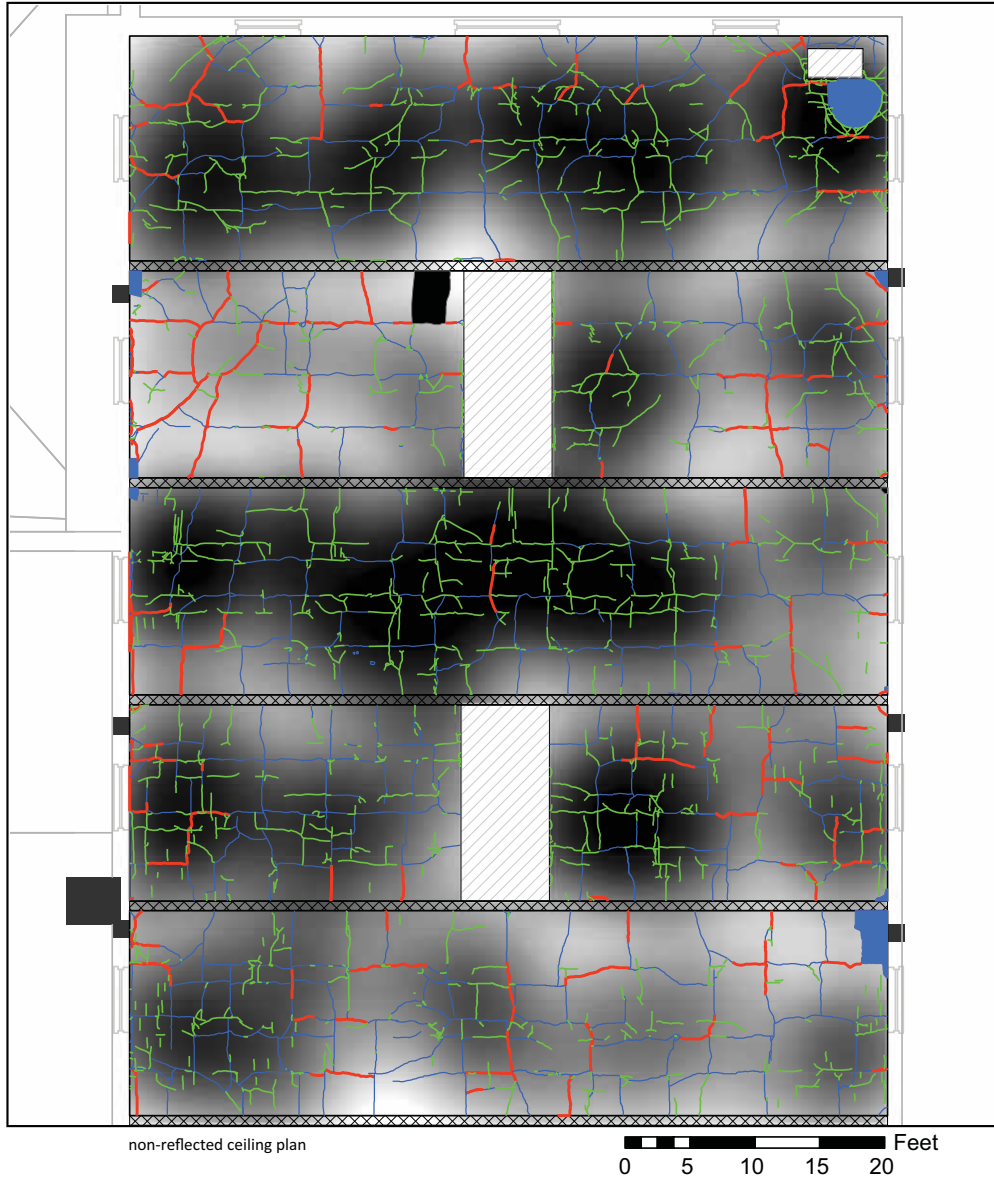
\*does not include separations along the truss

- Walls/Windows
- Chimney
- ▨ Skylights/Roof Hatch
- ▩ Truss

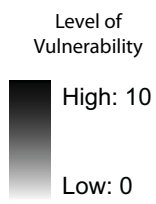


LOCATOR MAP

Map 13: Density of Small Cracks



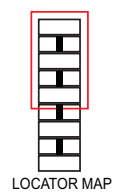
**LEGEND**



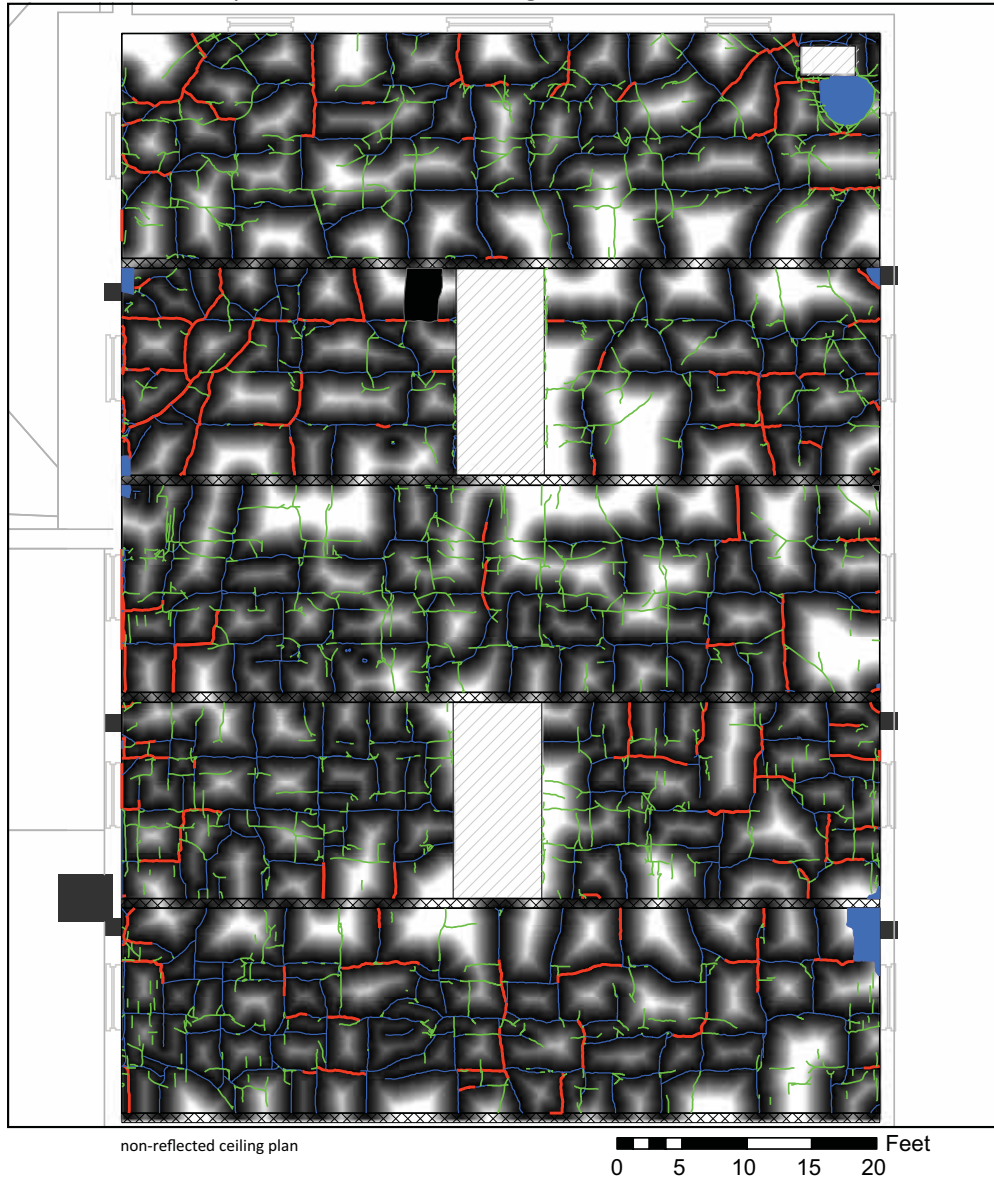
- Large Cracks
- Medium Cracks
- Small Cracks

- Previous Repair
- Total Loss

- Walls/Windows
- Chimney
- Skylights/Roof Hatch
- Truss



Map 14: Distance from Large and Medium Cracks



**LEGEND**

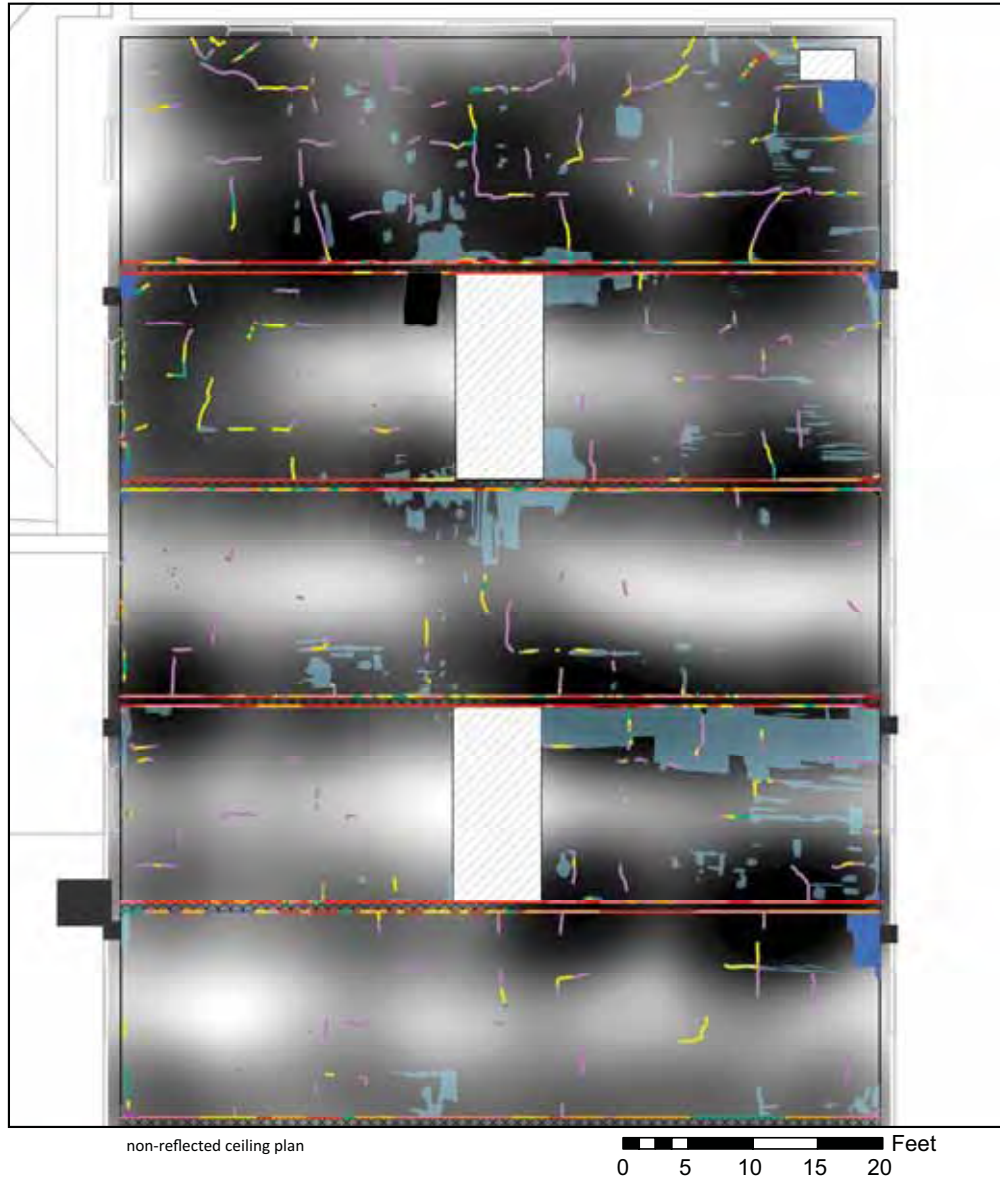
Level of Vulnerability High: 10 Low: 0	Large Cracks	Previous Repair
	Medium Cracks	Total Loss
	Small Cracks	
	Walls/Windows	Chimney
	Skylights/Roof Hatch	Truss

N

LOCATOR MAP

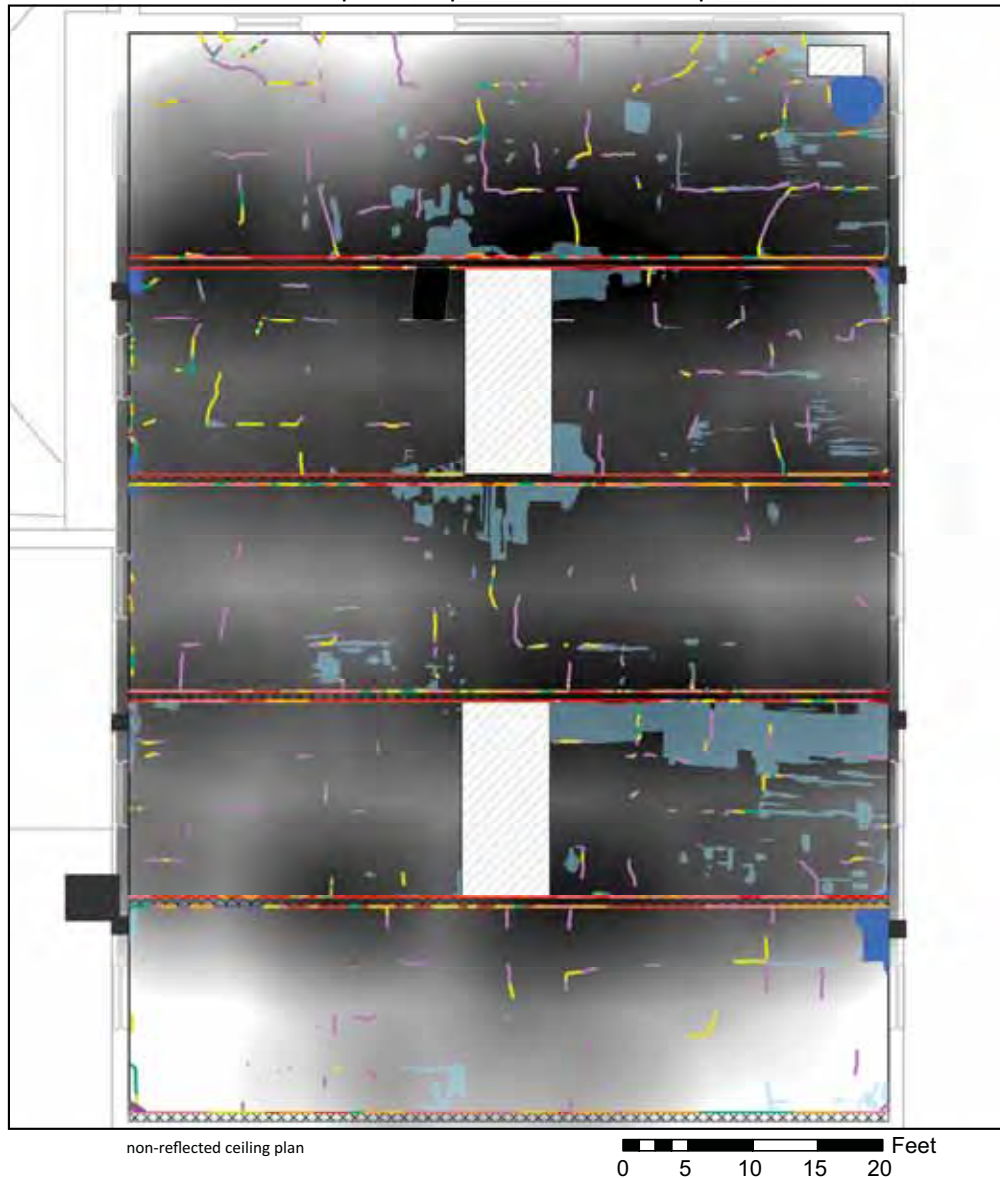
Map 15: Density of All Displacement





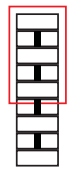
**LEGEND**

<p>Level of Vulnerability</p> <p>High: 10</p> <p>Low: 0</p>	<p>Displacement</p> <ul style="list-style-type: none"> <li><span style="color: red;">—</span> &gt; 20 mm</li> <li><span style="color: orange;">—</span> 10 &lt; 20 mm</li> <li><span style="color: yellow;">—</span> 5 &lt; 10 mm</li> <li><span style="color: green;">—</span> 3 &lt; 5 mm</li> <li><span style="color: cyan;">—</span> 2 &lt; 3 mm</li> <li><span style="color: blue;">—</span> 1 &lt; 2 mm</li> <li><span style="color: purple;">—</span> &lt; 1 mm</li> </ul>	<ul style="list-style-type: none"> <li><span style="background-color: blue; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Previous Repair</li> <li><span style="background-color: lightblue; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Water Staining</li> <li><span style="background-color: purple; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Partial Loss</li> <li><span style="background-color: black; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Total Loss</li> <li><span style="background-color: orange; border: 1px solid black; display: inline-block; width: 15px; height: 10px;"></span> Surface Accretion</li> </ul>	<p>N</p> <p>LOCATOR MAP</p>
	<ul style="list-style-type: none"> <li style="margin-right: 10px;"><span style="border-bottom: 1px solid black; width: 20px; display: inline-block;"></span> Walls/Windows</li> <li style="margin-right: 10px;"><span style="background-color: black; width: 15px; height: 10px; display: inline-block;"></span> Chimney</li> <li style="margin-right: 10px;"><span style="background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); width: 15px; height: 10px; display: inline-block;"></span> Skylights/Roof Hatch</li> <li style="margin-right: 10px;"><span style="background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); width: 15px; height: 10px; display: inline-block;"></span> Truss</li> </ul>		

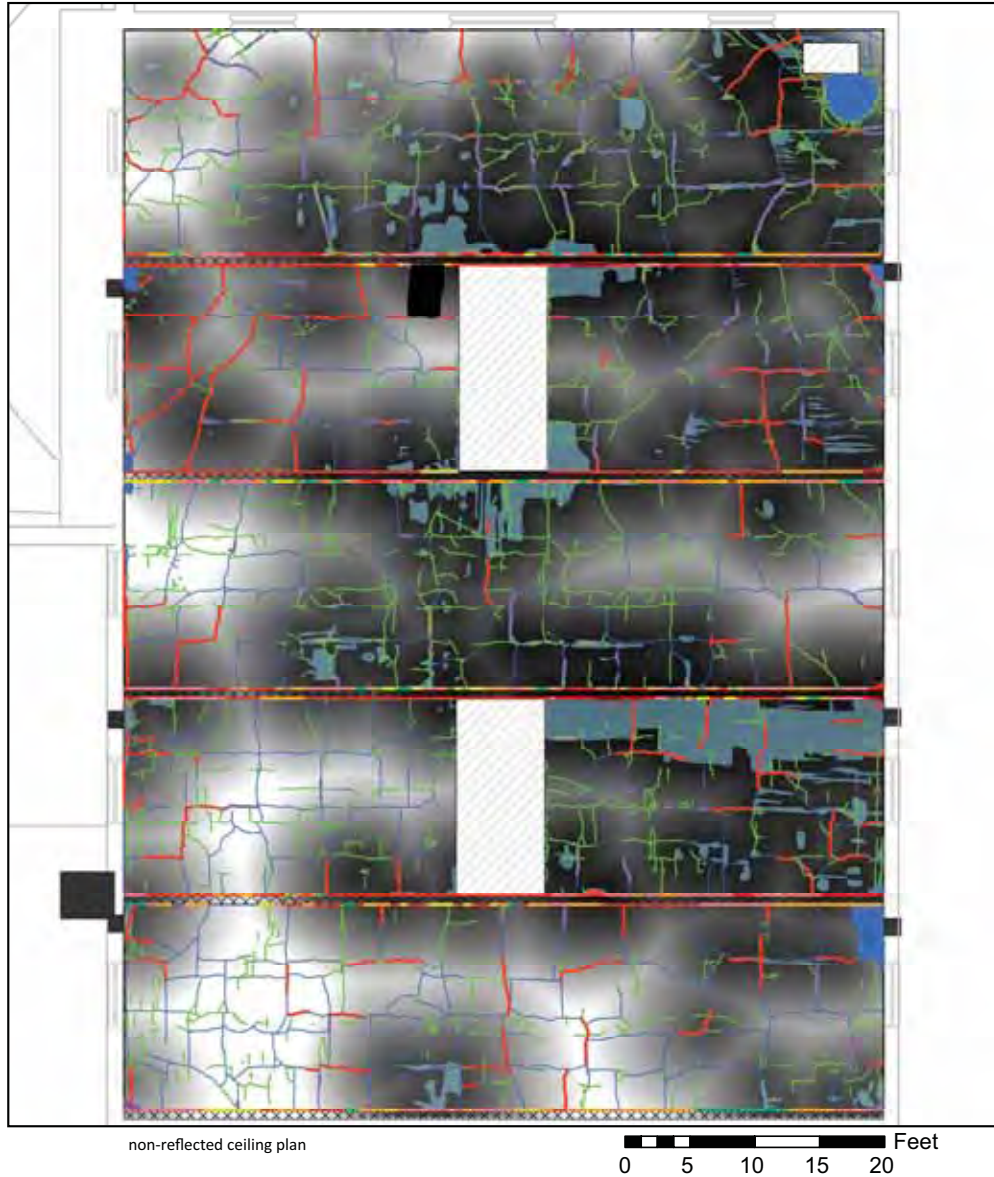
Map 16: Displacement Base Map



**LEGEND**

Level of Vulnerability  High: 10 Low: 0	<b>Displacement</b> > 20 mm 10 < 20 mm 5 < 10 mm 3 < 5 mm 2 < 3 mm 1 < 2 mm < 1 mm	Previous Repair Water Staining Partial Loss Total Loss Surface Accretion	Walls/Windows Chimney Skylights/Roof Hatch Truss	N   LOCATOR MAP
	> 20 mm 10 < 20 mm 5 < 10 mm 3 < 5 mm 2 < 3 mm 1 < 2 mm < 1 mm	Previous Repair Water Staining Partial Loss Total Loss Surface Accretion		

Map 17: Distance from Displacement and Water Staining

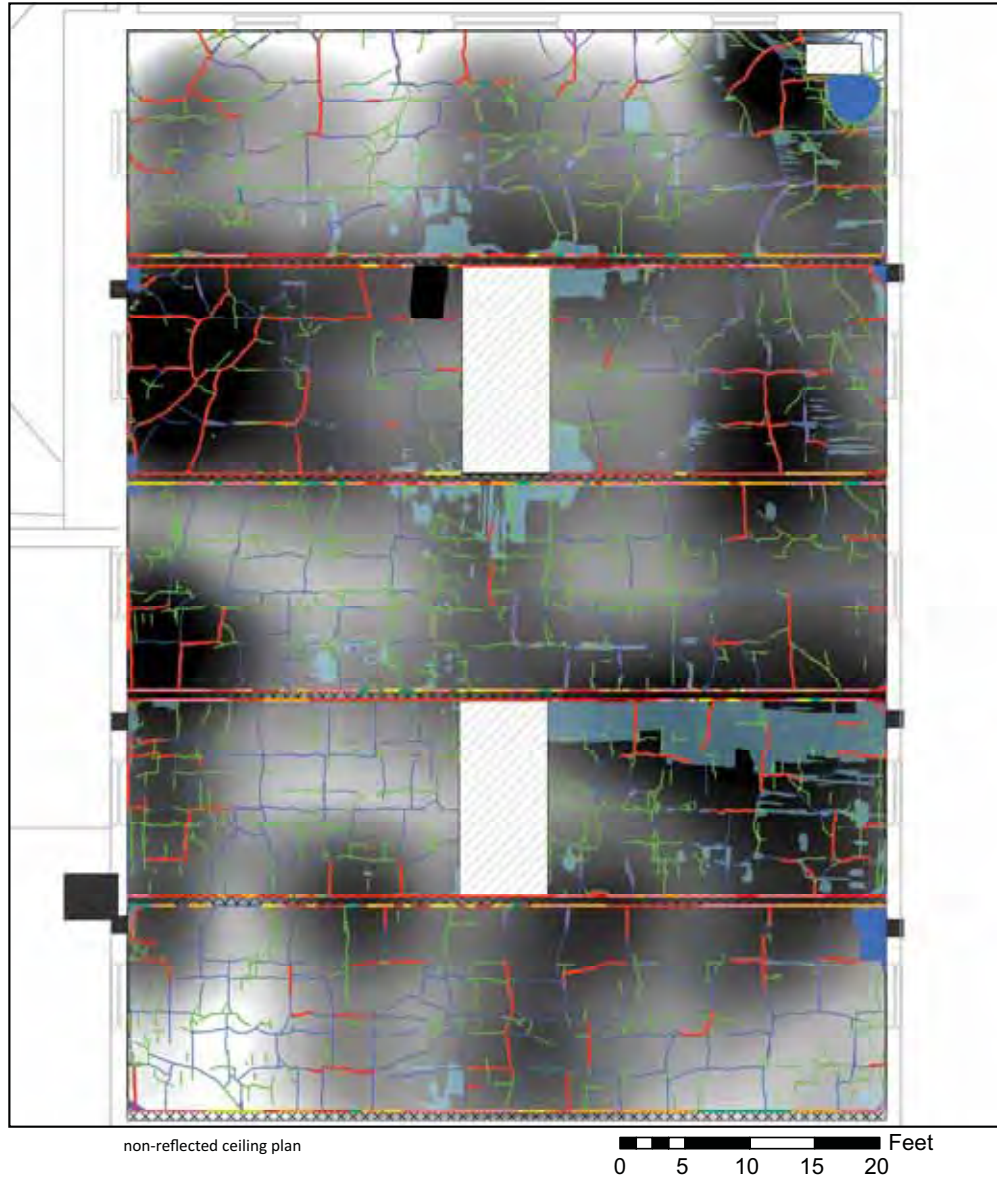


**LEGEND**

Level of Vulnerability High: 10 Low: 0	<b>Displacement</b> > 20 mm 10 < 20 mm 5 < 10 mm 3 < 5 mm 2 < 3 mm 1 < 2 mm < 1 mm	Large Cracks Medium Cracks Small Cracks	Previous Repair Water Staining Partial Loss Total Loss Surface Accretion	N   LOCATOR MAP
	Walls/Windows Chimney Skylights/Roof Hatch Truss			



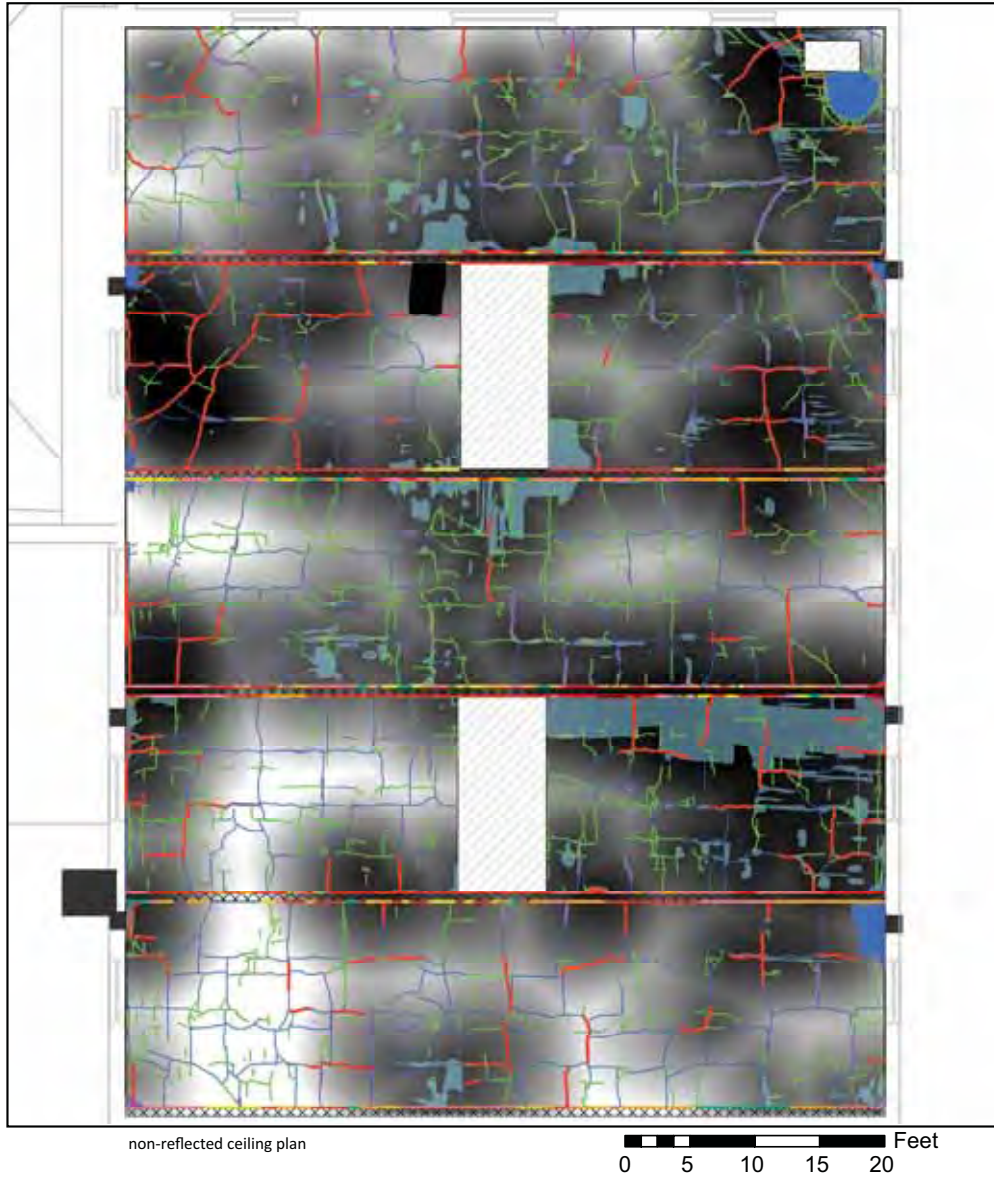
Map 18: Density of Large Cracks and Distance from Displacement





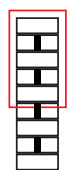
**LEGEND**

Level of Vulnerability High: 10 Low: 0	<b>Displacement</b> > 20 mm 10 < 20 mm 5 < 10 mm 3 < 5 mm 2 < 3 mm 1 < 2 mm < 1 mm	Large Cracks Medium Cracks Small Cracks	Previous Repair Water Staining Partial Loss Total Loss Surface Accretion	N   LOCATOR MAP
	Walls/Windows Chimney Skylights/Roof Hatch Truss			

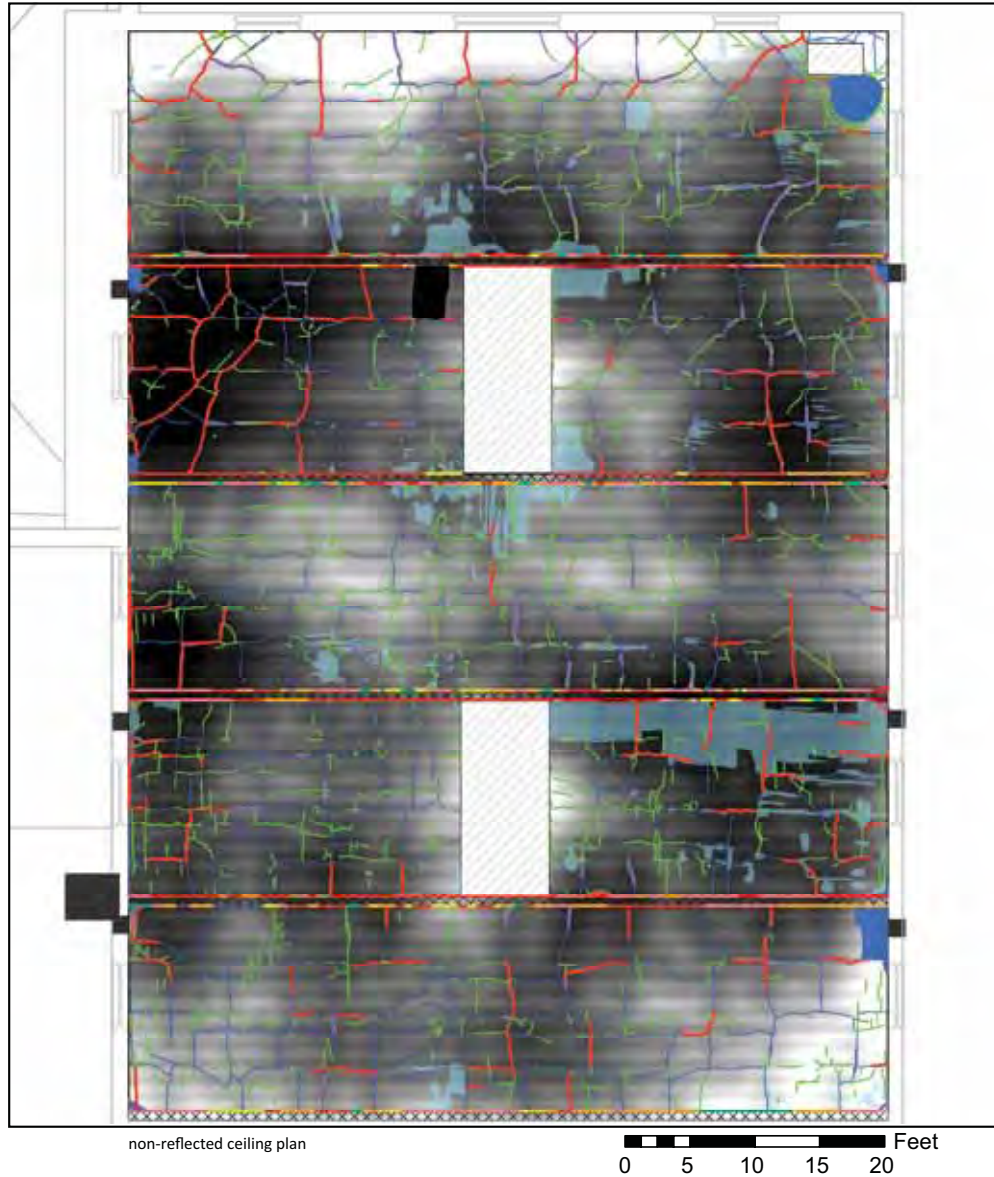
Map 19: Density of Large Cracks and Distance from Displacement and Water Staining



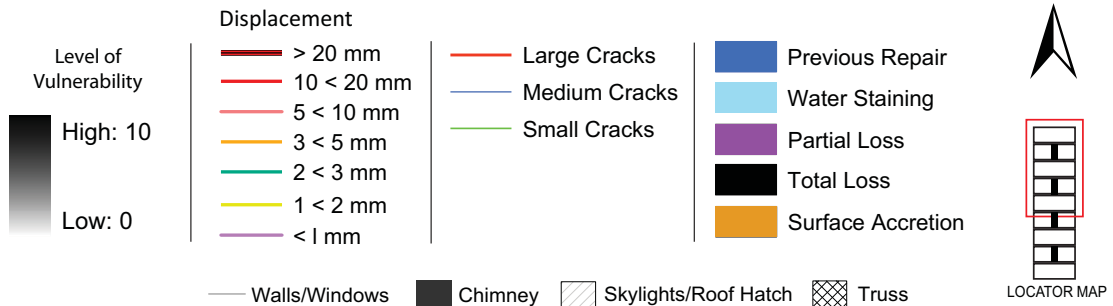
**LEGEND**

Level of Vulnerability  High: 10 Low: 0	<b>Displacement</b> > 20 mm 10 < 20 mm 5 < 10 mm 3 < 5 mm 2 < 3 mm 1 < 2 mm < 1 mm	Large Cracks Medium Cracks Small Cracks	Previous Repair Water Staining Partial Loss Total Loss Surface Accretion	N   LOCATOR MAP
	Walls/Windows Chimney Skylights/Roof Hatch Truss			

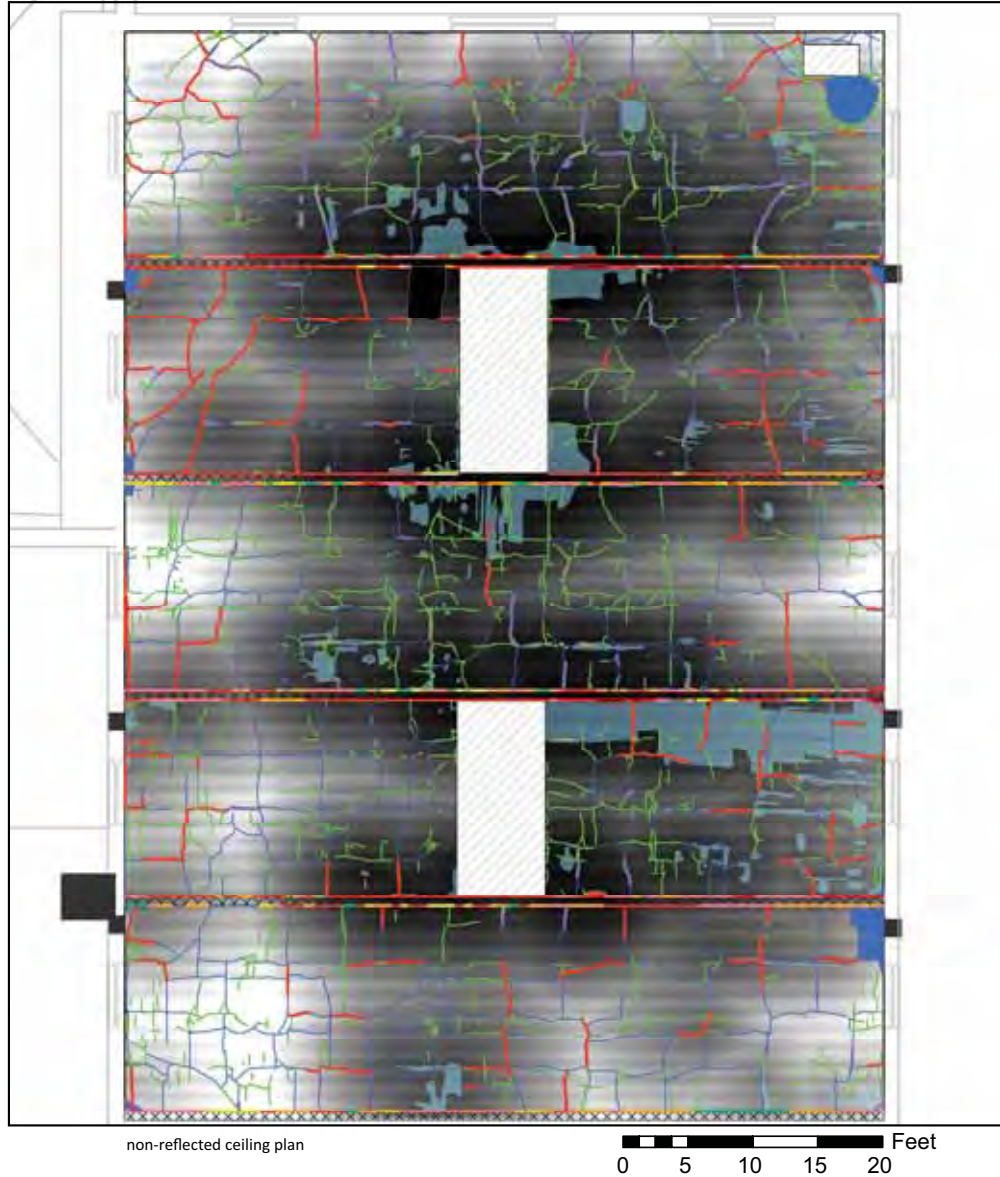
Map 20: Cause Map



**LEGEND**



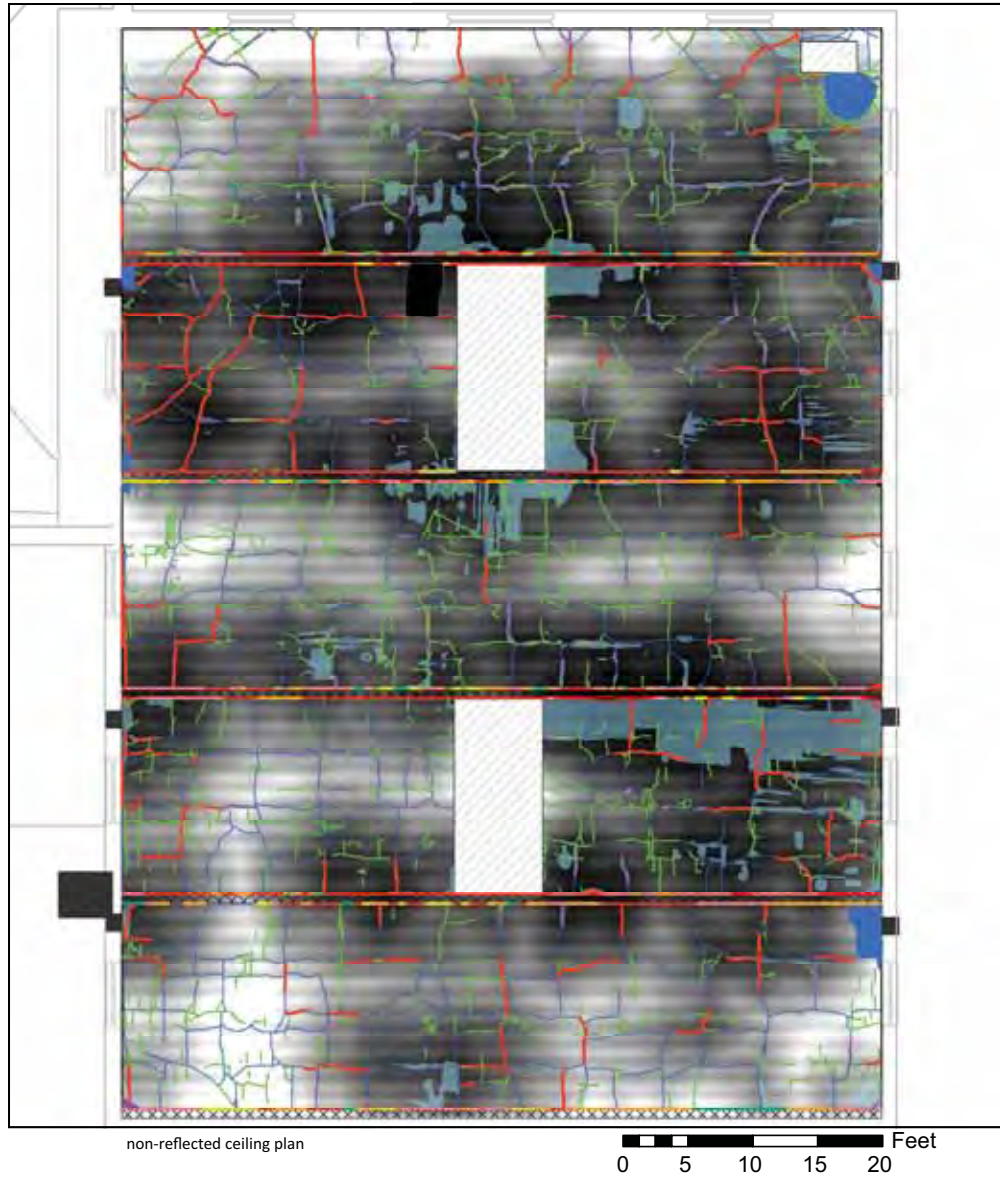
Map 21: Sympton Map



**LEGEND**

Level of Vulnerability High: 10 Low: 0	<b>Displacement</b> > 20 mm 10 < 20 mm 5 < 10 mm 3 < 5 mm 2 < 3 mm 1 < 2 mm < 1 mm	Large Cracks Medium Cracks Small Cracks	Previous Repair Water Staining Partial Loss Total Loss Surface Accretion	N   LOCATOR MAP
	Walls/Windows Chimney Skylights/Roof Hatch Truss			

Map 22: Combination Map



**LEGEND**

<p>Level of Vulnerability</p> <p>High: 10</p> <p>Low: 0</p>	<p><b>Displacement</b></p> <ul style="list-style-type: none"> <li><span style="color: red;">—</span> &gt; 20 mm</li> <li><span style="color: red;">—</span> 10 &lt; 20 mm</li> <li><span style="color: red;">—</span> 5 &lt; 10 mm</li> <li><span style="color: orange;">—</span> 3 &lt; 5 mm</li> <li><span style="color: green;">—</span> 2 &lt; 3 mm</li> <li><span style="color: yellow;">—</span> 1 &lt; 2 mm</li> <li><span style="color: purple;">—</span> &lt; 1 mm</li> </ul>	<ul style="list-style-type: none"> <li><span style="color: red;">—</span> Large Cracks</li> <li><span style="color: blue;">—</span> Medium Cracks</li> <li><span style="color: green;">—</span> Small Cracks</li> </ul>	<ul style="list-style-type: none"> <li><span style="color: blue;">■</span> Previous Repair</li> <li><span style="color: lightblue;">■</span> Water Staining</li> <li><span style="color: purple;">■</span> Partial Loss</li> <li><span style="color: black;">■</span> Total Loss</li> <li><span style="color: orange;">■</span> Surface Accretion</li> </ul>
	<ul style="list-style-type: none"> <li><span style="border-bottom: 1px solid black; width: 20px; display: inline-block;"></span> Walls/Windows</li> <li><span style="background-color: black; width: 15px; height: 10px; display: inline-block;"></span> Chimney</li> <li><span style="border: 1px dashed black; width: 15px; height: 10px; display: inline-block;"></span> Skylights/Roof Hatch</li> <li><span style="border: 1px dashed black; width: 15px; height: 10px; display: inline-block;"></span> Truss</li> </ul>	<p style="text-align: center;">N</p> <p style="text-align: center;">LOCATOR MAP</p>	

**Appendix B: Report from the Applied Research  
Laboratory, The Pennsylvania State University**

# THE USE OF SCANNING LASER DOPPLER VIBROMETRY FOR NON-DESTRUCTIVE EVALUATION OF STRUCTURAL FLAWS IN PLASTER

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*Applied Research Laboratory  
The Pennsylvania State University*

## **Abstract**

As historic buildings grow older, the condition of their plaster walls and ceilings continues to deteriorate. In order to develop an effective method to preserve these plaster structures, the integrity of the structure must first be determined. The objective of this work is to determine if Scanning Laser Doppler Vibrometry (SLDV), when used in conjunction with modal analysis techniques, is a viable method for detecting internal flaws in plaster walls and ceilings. Two different types of faults were investigated on plaster samples using this non-destructive testing method: detachment of the base coat of plaster from the wooden lath substructure and delamination of plaster layers from the base to finish coat. In order to study the modal properties of the plaster structures, the surfaces were first excited using a speaker and then later with a shaker system; both were driven by band-limited white noise. Frequency response functions were generated using the SLDV velocity fluctuation data from the plaster samples and compared to detect faults. It was discovered that local flaws in plaster structures do not generate significant enough changes in the global modal properties to identify different types of faults or their locations.

## **Introduction**

Current methods used to evaluate the structural integrity of plaster walls typically yield poor results, or are unable to determine the different types of faults. One method that is currently used is tap testing, which is a slow and labor intensive procedure that often leads to unidentified faults or false positives. Other methods, such as radar and thermography, are very good at detecting voids and moisture damage; however, they have not been used to detect faults such as plaster delamination and separation from the wooden lath. The shortcomings of these methods have led to the application of new technologies, such as non-destructive SLDV systems. The objective of this work is to determine if SLDV can

be used in conjunction with modal analysis techniques to locate and distinguish different types of faults in plaster structures.

Table 1: Plaster Sample Properties

Sample	Fault Type
A	None
B	Wood Lath Separation
C	Plaster Coat Delamination

### Experimental Methods

In this experiment, three 30 inch by 24 inch plaster ceiling samples were suspended above a scanning laser head, as shown in Figure 1. Each sample contained four separate faults that ranged in size from 1.5 - 2 inches in height and ran the entire width of the sample. These samples were then driven by band-limited white noise from 20-500 Hz using a Stanford Research DS345 signal generator, a Crown XTi 2000 amplifier, and a 12 inch speaker (See Figure 9 in Appendix A). A Polytech PSV 400 Scanning Laser Doppler Vibrometer was used to measure the velocity fluctuations of the plaster surface at 621



Figure 1: Scanning Laser Doppler Vibrometer System

different points, as shown in Figure 2. Using the data generated by the SLDV system, a frequency response function (FRF) was generated for each sample. The FRF's provided surface velocities as a function of frequency from 0 – 500 Hz. The FRF for samples B and

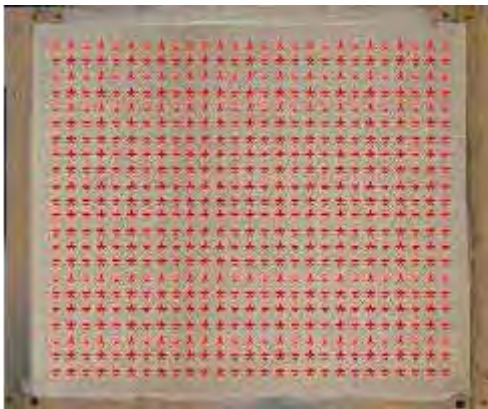


Figure 2: Laser Sampling Grid Superimposed on Sample

C were compared to sample A using a MATLAB® matrix subtraction in order to determine if fault locations could be detected. This experiment was repeated over a broader frequency range using a Wilcoxon Research F3 piezoelectric shaker as the excitation source. The shaker was driven by band limited white noise from 20 Hz – 5 KHz. For the shaker system, the FRF's provided surface velocities as a function of frequency from 0 – 2 KHz.



## Results and Discussion

When the results for the three plaster samples are compared, it can be seen that the FRF's are very similar in frequency, and many of the beam and plate modes were observed in the FRF's (See Figures 7A-7C in Appendix A). Between the range of 48 Hz and 54 Hz, the (1, 1) mode could be seen in every sample, and was easily distinguishable. This mode was measured at 53.8 Hz for Sample A, 51.3 Hz for Sample B, and 48.8 Hz for Sample C. The velocity magnitudes for every point on each sample were plotted in MATLAB® for the corresponding modal frequency, as shown in Figure 3. Using MATLAB®, Samples B and

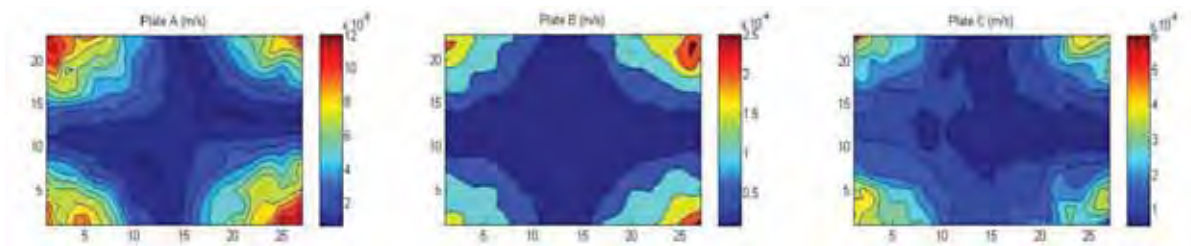


Figure 3: Velocity Distributions at Analyzed Mode: Sample A – 51.3 Hz, Sample B – 51.8 Hz, Sample C – 48.8 Hz (Speaker Excitation 20-500Hz)

C were then compared to Sample A. A MATLAB® code was used to subtract the velocity magnitudes for Sample A from Samples B and C. The results for Sample B-A and Sample C-A were plotted and are shown in Figure 4. As observed in Figure 4, there is no indication

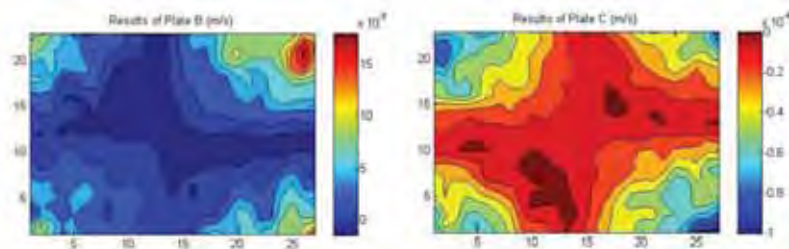


Figure 4: Comparisons of Sample B & C to Sample A (Speaker Excitation 20-500Hz)

of any types of horizontal faults in either Sample B or Sample C. The data is inconclusive as to the presence of the faults and where the faults are located. Due to the fact that the data is inconclusive, the experiment was performed again over a broader range of frequencies using an F3 piezoelectric shaker driven by band-limited white noise from 20 Hz – 5 KHz. When the results for the three plaster samples are compared from the shaker test, it is once again evident that the FRF's are very similar in frequency. Many of the beam and plate modes can again be seen in the FRF's (See Figures 8A-8C in Appendix A). Between the

range of 128 Hz and 134 Hz, the same mode was observed in every sample, and was easily distinguishable from any other mode. This mode was measured at 131.3 Hz for Sample A, 133.6 Hz for Sample B, and 128.1 Hz for Sample C. The velocity magnitudes for every point on each sample were then plotted for the corresponding modal frequency, as shown in Figure 5.

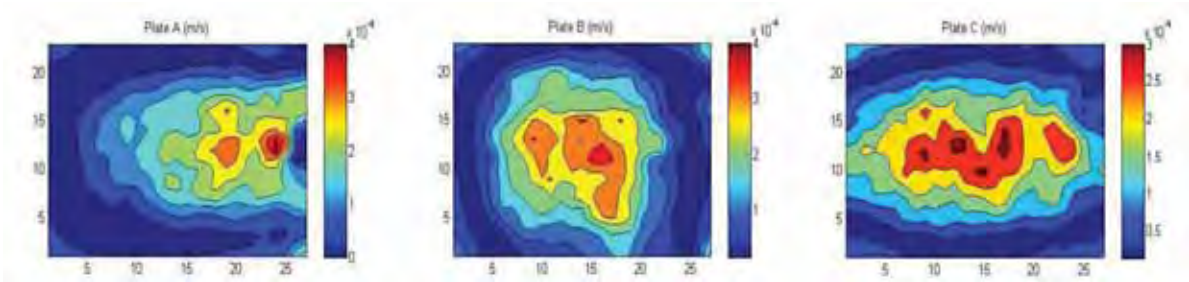


Figure 5: Velocity Distributions at Analyzed Mode: Sample A – 131.3 Hz, Sample B – 133.6 Hz, Sample C – 128.1 Hz (Shaker Excitation 20 Hz – 5 KHz)

Once again Samples B and C were compared to Sample A using a matrix subtraction. The results for Sample B-A and Sample C-A were plotted as shown in Figure 6.

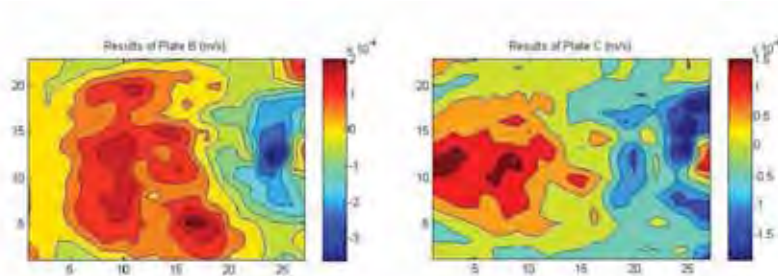


Figure 6: Comparisons of Sample B & C to Sample A (Shaker Excitation 20 Hz – 5 KHz)

The results from Figure 6 again show that there is no indication of any types of horizontal faults in either Sample B or Sample C. Thus, the data is again inconclusive as to what types of faults are present and where the faults are located.

## Conclusion

Using the SLDV and processing techniques described in this paper, the investigators were unable to detect faults in the plaster samples. Neither the speaker nor the shaker setups were able to generate large enough velocity differences at the fault locations to affect the overall global properties of the samples. There are many reasons that could lead to a lack of success.

The first is the variability between plaster samples since it is very difficult to create two samples that are identical in physical properties except for the intended faults. Therefore, a technique must be developed that compares the local properties of a plaster sample to its own global properties. This will eliminate sources of error due to manufacturing variability in samples. Second, it is possible that not enough energy was supplied to the plaster samples to excite a response at higher frequencies. Local defects may not have a significant effect on the global modal properties of a structure at low frequencies. However, local defects will likely have a more significant effect on the response at higher frequencies. In order to generate a response at higher frequencies, different excitation techniques must be used to supply sufficient energy to the structure at higher frequencies. With higher frequency equipment, it may be possible to detect the impact of the faults on the overall structural response.

### **Recommendations for Future Work**

The following recommendations may help in using SLDV to detect faults in plaster samples:

1. Use a different excitation source to generate a response at higher frequencies.
2. Develop a method that can compare the local properties of a sample to its own global properties.
3. Obtain a larger sample base with the same and combined faults, in order to determine the repeatability between the samples.

## Appendix A

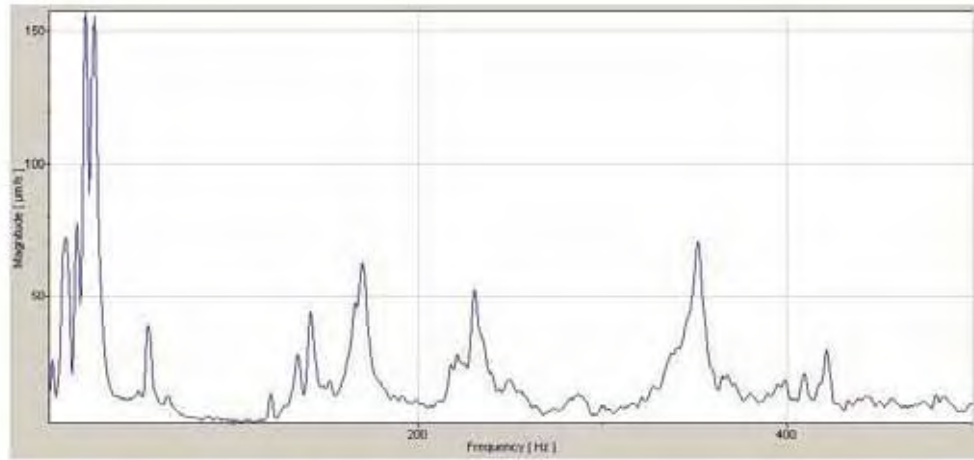


Figure 7A: Frequency Response Function of Sample A (Speaker Excitation 20 Hz – 500 Hz)

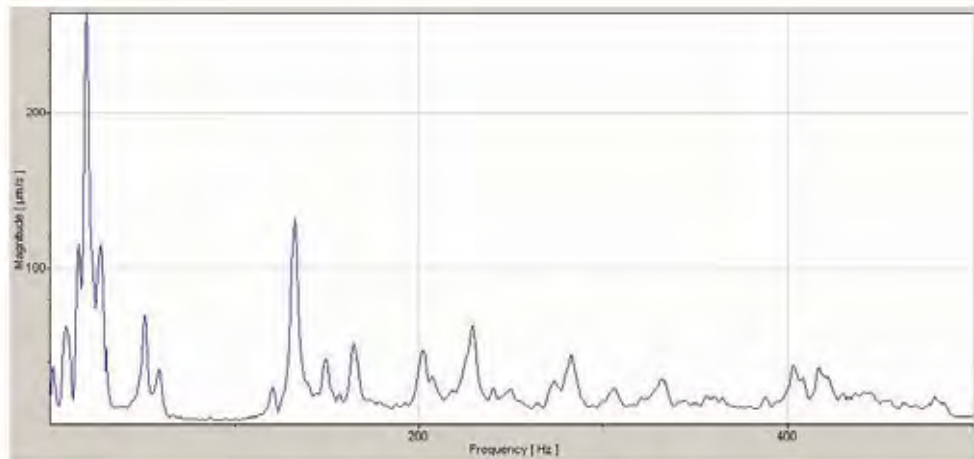


Figure 7B: Frequency Response Function of Sample B (Speaker Excitation 20 Hz – 500 Hz)

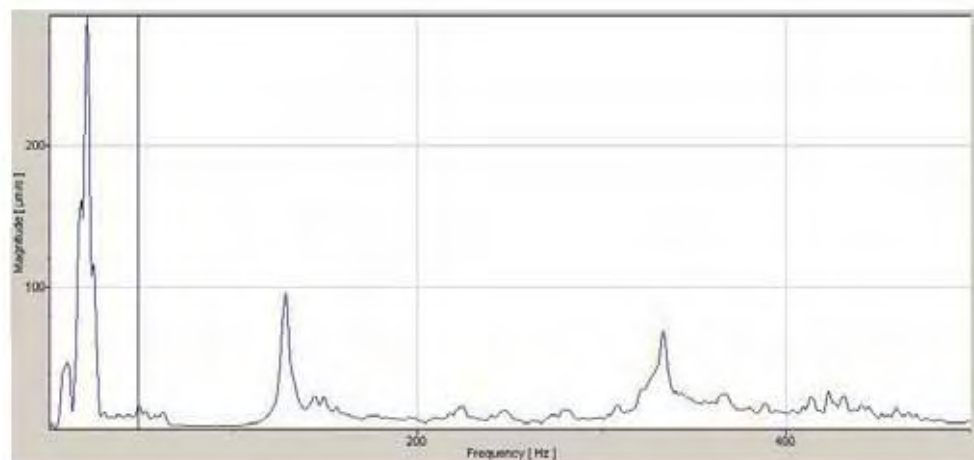


Figure 7C: Frequency Response Function of Sample C (Speaker Excitation 20 Hz – 500 Hz)

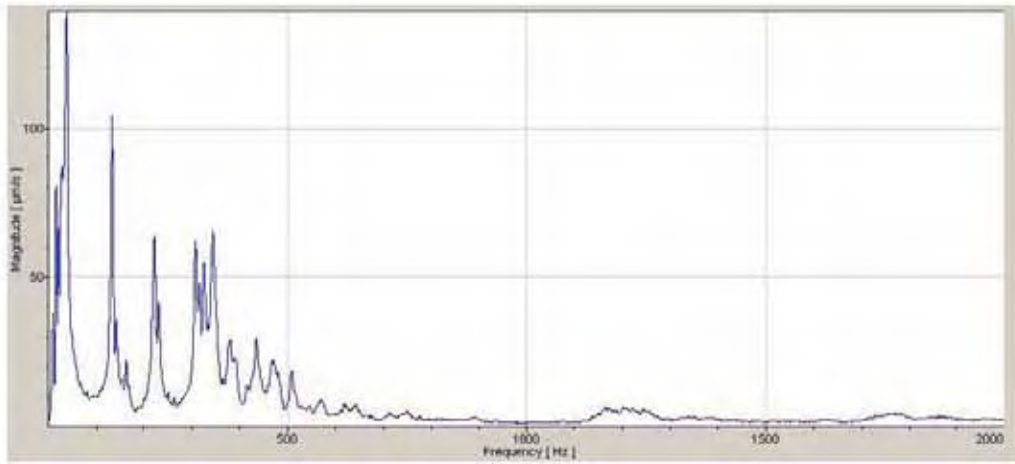


Figure 8A: Frequency Response Function of Sample A (Shaker Excitation 20 Hz – 5 KHz)

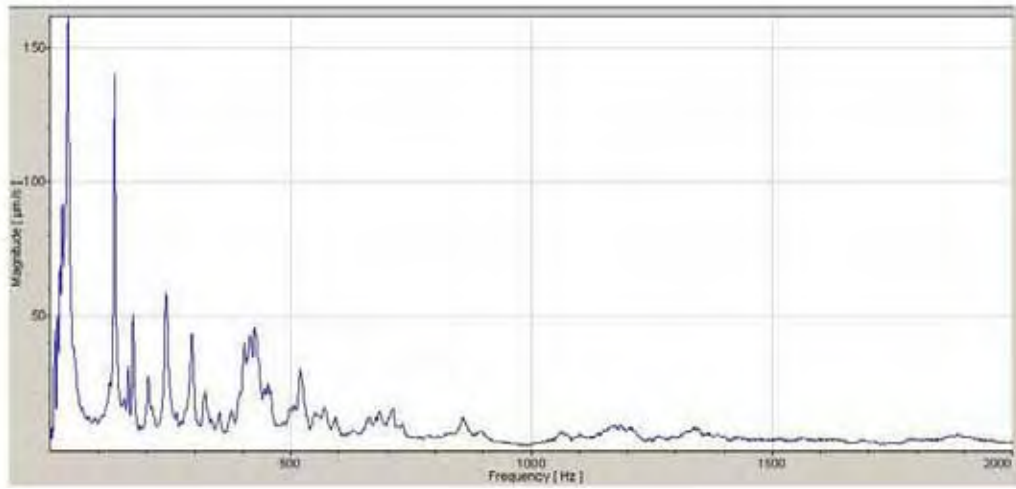


Figure 8B: Frequency Response Function of Sample B (Shaker Excitation 20 Hz – 5 KHz)

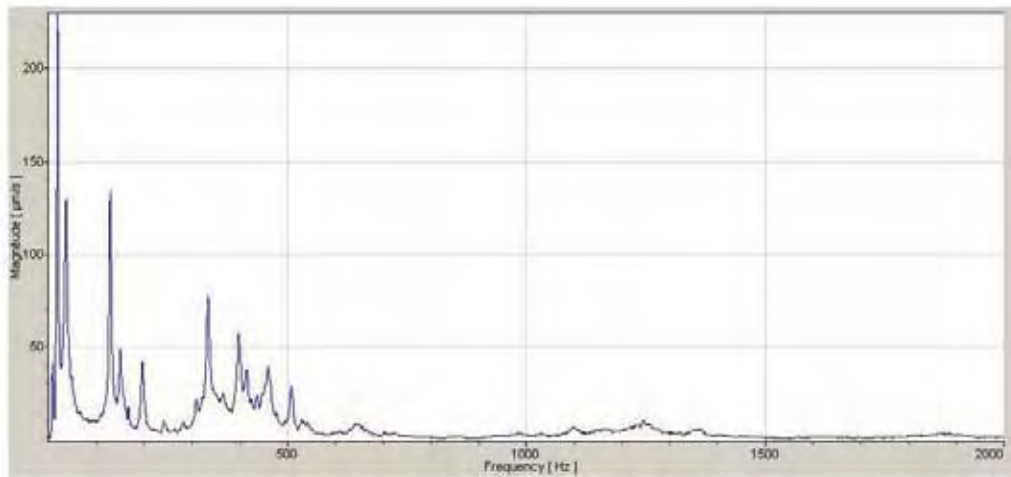


Figure 8C: Frequency Response Function of Sample C (Shaker Excitation 20 Hz – 5 KHz)



Figure 9: Excitation Sources Above Sample

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