# Testing the Flood Resilience of Traditional Building Assemblies

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How do materials used in flood-prone historic buildings in the United States fare when tested in a laboratory using modern methods and standards?


Fig. 1. Immersion chamber built by the U.S. Army Construction Engineering Research Laboratory for the study. Purified, heated water was stored in the blue drum. There is a temperature controller at the researcher's feet. A pump, not visible, circulated the water. There are three wall assemblies immersed in the chamber. Photograph by Mary Striegel, 2019.

Fig. 2. Wall assembly being lifted by hand. Note that the water was allowed to drain prior to setting the specimen aside to dry. A cover, constructed of plastic sheathing and PVC tubing intended to limit inward and outward contamination, has been removed and rests in the background. Photograph by Mary Striegel, 2019.

The National Historic Preservation Act directs the National Park Service (NPS), among other duties and responsibilities, to develop guidance and technical information on the preservation of historic properties.

The NPS published *Guidelines on Flood Adaptation for Rehabilitating Historic Buildings* in 2019 to assist property owners and managers of historic buildings within flood zones who are attempting to address the various requirements of building codes, zoning, flood insurance, and historic-preservation design review.[1] These guidelines were developed to provide information about how to adapt historic buildings to be more resilient to flooding risk in a manner that will preserve their historic character.

While researching the topic of flooding, it was determined that there was a significant lack of information on the performance of historic building materials on structures in the United States when they were inundated for an extended period of time. Building materials must be inundated for at least 72 hours to be officially designated as "flood damage–resistant" in the U.S. Anecdotal evidence suggests that many traditional building materials and assemblies fare well during a flood event. However, research into flood-resistant materials revealed that very little testing had been undertaken on how traditional buildings responded to floodwaters or how the materials in wall and floor assemblies performed when inundated with floodwater (existing research in the U.S. has been focused on building materials commonly used in new construction). Several European studies were consulted, but they focused on traditional materials less commonly used in the U.S., such as cob-wall construction, or the study was specific to local building traditions.[2] Those studies that did test historic assemblies or materials did not simulate floods over extended time periods.[3] Flood studies in the U.S. were generally limited to testing how modern buildings reacted to floodwaters.[4]

After investigating existing research on traditional materials and consulting scientists at the National Institute of Standards and Technology, the U.S. Department of Housing and Urban Development, and the Mitigation Division of the Federal Emergency Management Agency (FEMA), it was determined that little testing for flood resistance had been undertaken on historic building materials in the U.S.[5] In partnership with the U.S. Army Corps of Engineers, the NPS designed a study to test a variety of sample-sized traditional wall and floor assemblies. The assemblies were submerged in simulated contaminated floodwaters for a prolonged period (72 hours) and then removed to determine the ability of the different materials and assemblies to potentially dry out and be cleaned. The 72-hour inundation threshold was one of the benchmarks set by FEMA for testing to simulate the "prolonged contact with floodwaters" for "flood damage–resistant materials." The methodology for designing the study was influenced by a study of wall types in England; however, the NPS wanted to determine that this study would relate to U.S. building codes and regulations and to traditional building practices.[6]

## Approach

There are typically two possible approaches to evaluate resilience in traditional building materials: observational studies and experimental studies. Observational studies have the advantage of looking at buildings that have experienced real-world flooding under complex conditions. Observational research can be quicker if data is available. The disadvantage is the inability to ensure that the buildings have all had similar exposure. The work can be imprecise but can still provide relative information. Experimental studies have much more precision but may vary from real-world observations. Experimental work takes longer and may require more financial resources. The experimental approach was selected for this study. There are benefits to a "real-world" observational approach but controlling variables can prove extremely challenging. It was critical for this initial study to maintain control and knowledge of the materials and conditions, which together required a laboratory environment.

## Partner and Procedure Selection

In selecting a partner to run the test procedure, it was necessary to find a laboratory with a reputation for quality work and no real or perceived bias toward or against historic preservation. After considering several laboratories, the decision was made to partner with the U.S. Army Construction Engineering Research Laboratory (CERL), a part of the U.S. Army Corps of Engineers, Engineer Research and Development Center (ERDC).

A primary goal of the project was to ensure that the test results would be comparable to the results for modern substitute materials that are marketed as flood damage–resistant in the construction industry because there are restrictions in what materials may be used in construction once a flood has occurred. Flood insurance and local building code requirements factor into repair choices in the U.S. in several ways: Any property owner with a federally backed mortgage must maintain flood insurance; flood insurance is required for properties that receive federal disaster assistance after an event; and local ordinances and building codes have incorporated construction standards into their management of the floodplain.

Once a property suffers substantial damage in a flood and requires repair, federal regulations and local building codes may require that all new construction below the Base Flood Elevation (BFE) be constructed with "materials resistant to flood damage."[7] The National Flood Insurance Program (NFIP) publishes technical bulletins that assist in understanding the performance requirements. *Technical Bulletin 2: Flood Damage–Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program*, published in 2008, identified flood damage–resistant materials appropriate for use within the program.[8] Therefore, for this experiment, it was critical to use an established testing procedure that was widely recognized as providing a benchmark for product comparison. This led to the selection of *ASTM E3075-16: Standard Test Method for Water Immersion and Drying for Evaluation of Flood Damage Resistance*.[9]

*ASTM E3075* is the most applicable standard test for classifying building materials as acceptable or unacceptable for use below the BFE (Table 1). This testing protocol was created to identify performance specifications in order to determine if building materials and assemblies are resistant to water damage from flooding.[10] Many common new-construction materials have already been classified in FEMA *Technical Bulletin 2* as acceptable or unacceptable for use as either structural or finish materials.[11]

**Table 1. Class Descriptions of Materials from FEMA's *Technical Bulletin 2*.**

| NFIP category | Class | Class description |
|---|---|---|
| Acceptable | 5 | Highly resistant to floodwater damage, including damage caused by moving water. These materials can survive wetting and drying and may be successfully cleaned after a flood to render them free of the most harmful pollutants. Materials in this class are permitted for partially enclosed or outside uses with essentially unmitigated flood exposure. |
| | 4 | Resistant to floodwater damage from wetting and drying, but less durable when exposed to moving water. These materials can survive wetting and drying and may be successfully cleaned after a flood to render them free of the most harmful pollutants. Materials in this class may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection. |
| Unacceptable | 3 | Resistant to clean water damage, but not floodwater damage. Materials in this class may be submerged in clean water during periods of flooding. These materials can survive wetting and drying but may not be able to be successfully cleaned after floods to render them free of the most harmful pollutants. |
| | 2 | Not resistant to clean water damage. Materials in this class are used in predominantly dry spaces that may be subject to occasional water vapor and/or slight seepage. These materials cannot survive the wetting and drying associated with floods. |
| | 1 | Not resistant to clean water damage or moisture damage. Materials in this class are used in spaces with conditions of complete dryness. These materials cannot survive the wetting and drying associated with floods. |

However, FEMA's information is not complete and does not include the majority of traditional materials that were used in historic building construction. Even those materials that may be similar, such as brick, were classified based upon tests of modern materials (such as high-fired extruded brick rather than traditional lower-fired handmade brick). There may be differences in performance between traditional materials and their modern counterparts that could impact the suitability of existing materials for continued use or in-kind replacement in flood-prone areas.

*Technical Bulletin 2* includes provisions for the use of other materials below the BFE. These materials must be evaluated for suitability, and a final determination for a specific application is determined by a local official. Local community or state performance requirements may exceed those required by the NFIP. All applicable standards of the state or local building codes must be met for any structure requiring repairs in the special flood-hazard area.[12]

The original intent of the NPS program was to provide information that could be used for such evaluations of historic buildings within special flood-hazard areas that were undergoing renovations and attempting to meet modern building code requirements or retain flood insurance. While some promising results for historic materials and their flood resistance were found, testing showed the potential variables and testing protocols that could be altered to result in more reliable conclusions.

## Materials Tested

After a property has been flooded, the property owner or manager must make many decisions regarding the impacted materials. Some materials can be cleaned or refinished and remain in place; other materials must be replaced due to structural failure or the inability to sufficiently clean or repair them to pre-flood conditions. For owners of historic properties, there is often an added layer of concern due to the typical preservation practice of replacing damaged materials so that they match the historic material and appearance in order to preserve the historic integrity of a building. It is also important to evaluate whether these recommendations may lead to future damage to the building or to unsustainable practices as properties may continue to flood.

This test was designed to provide some answers for property owners of historic buildings. There is no opportunity to control the construction or installation methods of materials unless the building is undergoing significant renovation. Since it was important to attempt to replicate real-world conditions as closely as possible, it was decided to test wall and floor assemblies rather than isolated materials.

The assemblies used in this series of laboratory tests were selected to represent a sampling of historic methods and materials frequently used in buildings dating from the mid-nineteenth century through the early twentieth century. Particular attention was given to utilizing old-growth wood and identifying appropriate historic masonry materials (bricks, mortar mixes, and plasters) in order to approximate flooding effects upon a myriad of common historic construction typologies. To ensure historic veracity in the construction of the assemblies chosen for testing, a number of late nineteenth- and early twentieth-century handbooks and construction manuals were consulted to create assembly specifications. A preservation architect verified the specifications and added technical details to ensure that the test samples would provide the closest possible approximation of historic wall and floor assemblies.

A total of 16 assemblies were tested; they consisted of five masonry walls, seven wood-frame walls, and four floor types (Table 2). Terrazzo flooring was not tested because it is already included

**Table 2. Traditional Assemblies Constructed for Resilience Testing.**

| Brick walls | Description | Construction methods |
|---|---|---|
| Wall A | Traditional brick assembly | Handmade brick wall with lime-putty mortar. The interior had three-coat plaster applied directly to the brick. |
| Wall B | Early twentieth-century masonry assembly | An extruded structural clay-tile wall with extruded brick veneer assembled using galvanized-steel masonry ties with portland-cement and hydrated-lime mortar. |
| Wall E | Traditional brick assembly modified with insulation and gypsum wallboard interior | Wall A construction with spray foam. The interior was finished with gypsum wall board, joint compound, primer, and latex paint. |
| Wall I | Traditional brick assembly with limewash | Wall A construction. The interior was finished with plaster applied directly to the brick and coated with oil-based lead-carbonate paint. The exterior was limewashed with a lime putty and water mixture. |
| Wall J | Traditional brick assembly with wood wainscot | Wall A construction. The interior was finished with wood wainscot attached to wood nailing blocks embedded in the masonry coated with oil-based lead-carbonate paint. |

| Wood-frame walls | Description | Construction methods |
|---|---|---|
| Wall C | Wood-frame assembly | White pine wood-frame wall nailed together with lap siding attached directly to wall studs. The interior had three-coat plaster lacking sheathing applied over re-claimed wood lath. The baseboard was attached directly to the frame and painted with oil-based lead paint. |
| Wall D | Wood-frame assembly with sheathing | Wall C construction. The exterior had reclaimed Southern yellow pine Dutch lap siding attached to diagonal sheathing. |
| Wall F | Wood-frame assembly with clapboard and wire lath | Wall C construction. The interior was finished with two-coat plaster applied over self-furring metal lath. The baseboard was attached directly to the frame. |
| Wall G | Wood-frame assembly with aluminum siding | Wall C construction. The exterior had aluminum siding atttached directly over unpainted clapboard. |
| Wall H | Wood-frame assembly with mineral-wool insulation | Wall C construction. The cavities between the framing boards were filled with mineral-wool insulation. The interior had three-coat plaster applied over reclaimed wood lath. The interior was painted with oil-based lead paint. |
| Wall K | Wood-frame assembly with stucco | Wall C construction. The interior had two-coat plaster applied over self-furring metal lath and painted with oil-based lead paint. The exterior had three-coat stucco applied over self-furring metal lath on reclaimed oak diagonal sheathing. |
| Wall L | Wood-frame assembly with wainscot | Wall C construction. The interior had reclaimed beadboard wainscot attached directly to the wood frame and painted with oil-based lead paint. The exterior had reclaimed clapboard siding attached over reclaimed oak diagonal sheathing using 6d nails. |

| Floors | Description | Construction methods |
|---|---|---|
| Floor A | Heart pine | Heart pine tongue-and-groove flooring (rift and quarter-sawn). Half of the floor was finished with oil-based floor wax; the other half was finished with tung oil. |
| Floor B | Cypress | Cypress tongue-and-groove flooring (plain sawn). Half of the floor was finished with shellac; the other half was finished with tung oil. |
| Floor C | Ceramic tile | 2-by-2-inch white ceramic tile. The concrete slab was unreinforced limestone and portland cement. Tiles were set and grouted with portland-cement and lime mortar. |
| Floor D | Oak with sheathing | Oak diagonal subfloor with 2-by-1-inch oak tongue-and-groove flooring (rift sawn) finished with shellac. |

in *Technical Bulletin 2* as a class 4 material, meaning it is acceptable as a floor finish where flooding is likely to occur.[13]

Masonry wall assemblies followed early nineteenth-century American construction (handmade brick and lime mortar) and early twentieth-century construction (extruded brick, structural clay tile, and a combination lime and portland-cement mortar). Variations of the early American masonry wall were also tested to learn how the application of insulation, stucco, or different interior finishes might affect performance. The portland-cement mortar and stucco mixes were closest to *ASTM C270: Standard Specification for Mortar for Unit Masonry*, Type M with a 3:1 sand-to-cement ratio with 15 percent hydrated-lime replacement of cement.

Wood-frame walls were constructed using salvaged, old-growth, quarter-sawn white pine wood, likely Western white pine (Western and Eastern white pine cannot be differentiated through microscopic analysis). These wood frames were utilized in Walls C, D, F, G, H, K, and L.[14] Anecdotal evidence had indicated a potential difference between assemblies that had exterior sheathing from those with clapboard applied directly to the studs. The Dutch lap, or novelty siding, used in Wall D was made of Southern yellow pine. Wall F also used white pine, likely Eastern white pine.[15] Variations of the wall assemblies with common alterations found in historic districts were included, such as aluminum siding layered on top of exterior wood siding and mineral-wool batt insulation filling the cavity.

Common traditional interior finishes of plaster, wood trim, and wood wainscot were used with both the masonry and the wood-frame walls. Plaster was applied directly to masonry or applied to wood or metal lath. The three-coat plasters used United States Gypsum Corporation (USG) Red Top gypsum plaster. The scratch and brown coats had an approximate 1:3 ratio of plaster to sand. The finish coat was Red Top gypsum plaster only. Red Top is composed of more than 95 percent by weight plaster of Paris (calcium sulfate hemihydrate). All interior finishes were painted with oil-based lead paint, which is a natural fungicide. Although such paint is not common in modern construction, it still exists in many historic buildings beneath more modern latex paints.

Floor assemblies included three types of traditional wood floors on wood framing. Two samples tested the difference between heart pine and cypress as examples of nineteenth-century American flooring structures with wide-plank, tongue-and-groove flooring nailed directly to joists. The heart pine was rift or quarter-sawn, and the cypress was plain sawn. The third flooring assembly—narrow oak boards nailed to a subfloor—was intended to replicate the common flooring of the later nineteenth and early twentieth centuries. Wood floors were finished in traditional ways with tung oil, floor wax, or shellac, with some test samples using two of the finishes on the same sample (one finish on each half of the floor). Finishes were allowed to oxidize for 17 weeks to allow for hardening. The final floor type was ceramic tile on a concrete subfloor with a portland-cement and lime grout, similar to that used in many first-floor commercial buildings from the early twentieth century.

Researchers at CERL sourced the materials and constructed each sample wall and floor assembly according to the specifications created by the NPS. Masonry walls, plaster, and stucco were cured for a minimum of 30 days.

## Test Design and Apparatus

To be economical in the testing method, it was necessary to size the sample wall and floor assemblies so that they would adequately reflect real-world scenarios but allow testing of several samples at one time. Similarly, the immersion tank was constructed at a reasonable size to immerse samples according to the requirements of *ASTM E3075* with a manageable amount of water (Fig. 1).

Test samples were constructed with wall samples nominally at 3 feet by 3 feet and floor samples approximately 16 inches by 16 inches. An immersion chamber was created by CERL researchers from a galvanized-steel watering trough (8 feet by 2 feet by 2 feet), which was fitted with small bulkhead ports at opposing corners to facilitate water movement throughout each testing period. An aquarium chiller and heater controlled the temperature of the water, which was circulated by a pump. Working in concert, the heater and chiller maintained the specified water temperature of 75±5°F. Researchers also constructed a containment tent using PVC pipe and plastic sheeting, which could fit over the whole immersion chamber to mitigate cross-contamination with other areas of the laboratory.

## Test Procedure

The same procedure was conducted for the six groups of assemblies. The number of groups was determined by the number of test samples that could fit within the immersion chamber. Before immersion, each test sample was stored in a climate-controlled environment until an equilibrium weight could be observed. A store of filtered tap water meeting the ASTM requirements of 95 percent chlorine and fluorides removed, a pH of 6.0 to 9.0, and a temperature of 75±5°F provided the base for creating simulated floodwaters. Sewage and mold surrogates, with a nutrient broth, were added to filtered tap water.[16]

Wall samples were tested in a vertical orientation with approximately 50 percent of the assembly below the water level. Flooring samples were tested in a horizontal orientation and were completely submerged at least one inch below the surface of the water. The immersion period for each group was 72 to 80 hours in duration. Throughout that time, the water was continuously circulating to maintain the temperature of the water within a range specified by *ASTM E3075*. The water movement was minimal and not intended to simulate the forces of floodwater on the specimens.

At the end of the immersion period, the test samples were removed from the water and allowed to drain. Masonry wall samples were lifted into and out of the immersion chamber by a crane, while all other samples were lifted by hand. Some specimens weighed an excess of 200 pounds (Fig. 2).

Within one hour of removal from the water, the samples were weighed to determine how much water had been absorbed. Samples were allowed to dry within a controlled environment and weighed periodically until a final equilibrium weight was achieved.[17] The duration required to reach that weight was recorded.

Once dry, the accessible surfaces of the assemblies were cleaned using microfiber cloths or non-metal scrub brushes and antimicrobial soap and potable tap water. Finally, swabs of various surfaces were taken for analysis to determine the presence or absence of surviving sewage and mold surrogates.

## Evaluation

Each test sample was evaluated based on three aspects of performance: weight measurements to determine water absorption and drying, visual alterations and degradations, and swab results to determine contamination after cleaning.

The percentage increase in the weight of each sample was an indication of the porosity of the materials used to construct the assemblies; a lower percentage indicates better resistance to water absorption. The drying time is represented by the number of days observed for an assembly to reach its final weight. An important consideration of this aspect of the test is that it was conducted during winter in Champaign, Illinois. The relative humidity within the laboratory was lower than the recommended range of 50±5 percent in *ASTM E3075* and may have shortened drying times. Relative humidity levels vary greatly throughout the U.S., and the ASTM test does not take into account this variation.

Visual observations were aided by photographs and written remarks for each sample assembly taken throughout the process. *ASTM E3075* specifically mentions taking note of changes to the specimen. These can be changes in physical dimensions, indicating swelling of the material, or altered appearance, such as staining that cannot be cleaned. *Technical Bulletin 2* defines flood damage–resistant materials as those that "withstand direct and prolonged contact with floodwaters without sustaining significant damage." The FEMA definition of "prolonged contact" is 72 hours; FEMA describes "significant damage" as anything requiring more than cosmetic repair, which can include cleaning, sanitizing, and resurfacing a material. Resurfacing is described as including activities such as sanding, joint repair, and repainting. Visual observations focused on problems indicating that significant repairs might be required, such as cracking, warping, or detachment of materials from the assembly. Staining that could not be removed was also noted since it is directly mentioned in the test standard, although it seems more cosmetic in nature.[18]

A total of 112 swab samples were taken across the 16 assemblies to test for remaining *E. coli* and fungi after cleaning. Swabs were collected according to *ASTM D7789: Standard Practice for Collection of Fungal Material from Surfaces by Swab* and analyzed by an external laboratory within three days of receiving the swabs.[19] The fungal counts were at the detection limits of the analysis. Thus, all reported results in the fungal count category are statistically the same and did not influence the material classification recommendations made by CERL researchers. The other two categories of analysis, representing *E. coli* survival and total coliform, did influence the recommendations.[20]

## Conclusions

**Limitations of testing.** This first test experience has provided many lessons that the NPS seeks to improve upon during future rounds of testing. In the event that others plan to undertake similar testing, it is important to share the following issues and problems that were discovered along the way.

**Challenges with materials and the construction of sample assemblies.** Every effort was made to source salvaged historic materials or modern equivalents that were manufactured using traditional materials and methods. However, it is not possible to replicate all conditions of a historic structure. Historic construction relied on local materials and local traditions. For example, bricks were made from local clay and fired at various temperatures, resulting in vastly different properties. No single test will lead to a universal conclusion. For historic assemblies, it may be necessary to do more preliminary analysis of the specific materials, such as wood-species testing, to understand the results.

Due to scheduling and contracting deadlines, it was not possible to allow for a longer cure time for masonry and plaster materials. Professionals, researchers, and students who are knowledgeable about the lime cycle will know that 30 days is insufficient to replicate the properties of historic plaster or mortar that has been extant for years or decades.[21] Also, none of the assemblies were constructed by tradespeople skilled in traditional crafts. Maintaining historic buildings is an element of flood protection. The samples, while not perfectly sealed or crafted, likely replicate buildings that are poorly maintained, although that was not the original intent. It is unknown if the lack of traditional building skill during assembly could influence the performance. It is worth noting that in the nineteenth and twentieth centuries, there was a great variety in the skill level of the tradespeople constructing buildings.

**Movement of test samples into and out of the flooding tank.** The design of the immersion chamber required that test samples be lifted into and out of the tank. Lighter-weight flooring and wood-frame walls were lifted in and out by hand. Heavier masonry wall samples were transported by a crane and steel lifting hooks. Lifting eyes or handles would aid future work as long as they are included in the initial weight. Despite precautions, such movements are quite likely to cause unusual stress points, deflections, and vibrations that could result in physical damage to the assembly. Therefore, some of the observed visual conditions could be attributed to either the flooding or the movement of the test specimens (Fig. 3).

**Low relative humidity for drying.** Although the laboratory where the testing was conducted was temperature-controlled, relative humidity could not be as closely regulated. It was low for the duration of the test, which could have affected both the drying time and swab results. The low humidity may have contributed to the relatively fast drying times (most specimens reached equilibrium in less than 30 days) and to the warping of wood elements as the result of differences in radial, tangential, and longitudinal shrinkage.

## Test Results

Although there are improvements that can be made to the materials preparation and the testing procedure, the results of this first test provide some initial indications of how various traditional materials perform during a 72-hour flood. Full results and data are available in the U.S. Army Corps of Engineers report entitled *Flood Resilience of Traditional Building Materials*. This report includes specific weight, swab, and visual analysis for each assembly tested, as well as recommendations from CERL researchers for the classification of materials according to *Technical Bulletin 2* categories of performance (a five-category scale).[22]

Ceramic tile, high-fired extruded brick, and structural clay tile performed very well, taking on little water, cleaning easily, and resulting in low microbial activity. The handmade bricks performed at a level classified by researchers to be acceptable for applications below the BFE, although the porosity of the brick is some cause for concern, due to the unknown elements of potentially contaminated floodwaters and the challenge of thoroughly cleaning a permeable surface.

Limewash that has been adequately cured shows excellent resilience to floodwater. Historically, limewash was used for its antiseptic properties; thus, it is not surprising that it inhibited biological activity.[23] Likewise, lime mortar showed little microbial activity, which is likely due to its high pH, making it unlikely that bacteria could survive. However, the mortars in all of the masonry walls were somewhat problematic. The mix including portland cement did not perform at the same level that FEMA had categorized the material in prior tests. The mortar was permanently stained, and it wicked water to the top of the wall assembly. Lime-based mortars also wicked water to the tops of the wall samples, cracked, and showed signs of structural failure. As noted in the limitations above, some of these structural issues could have been due to the movement of the wall samples rather than the flooding itself. It may also have been due to poor craftmanship or inadequately cured mortars. Cracking in the mortar is a condition that can occur in real-world examples and is commonly repaired through tuckpointing. It may not be realistic to judge historic masonry that has been inadequately maintained as flood-resistant, but masonry buildings in various states of repair have withstood multiple floods when allowed to dry and be repaired. More research is needed.

The primary lesson learned from the wood-frame assemblies is that any cavity wall that is inundated, no matter the materials (including those classified as acceptable in FEMA *Technical Bulletin 2*), will be problematic due to the lack of adequate access to clean each flood-impacted surface without disassembly. In general, more layers of materials translated to more water absorption and drying time, as well as more surfaces that harbored bacterial growth that had not been neutralized by FEMA-recommended cleaning procedures (Table 3). Common practice is to require the removal of historic finishes to access wall cavities to allow moisture to dissipate.

Floor assemblies performed relatively well, with the exception of the oak flooring on a diagonal-board subfloor. Again, inability to access all surfaces for cleaning and drying is a problem in any layered assembly that is inundated. Indications from this test confirm anecdotal evidence that traditional floor systems without a subfloor can be dried, cleaned, and refinished for continued use after a flood. Drying times may differ based on regional variables for humidity. Areas with high humidity after a flood will likely require additional drying time.

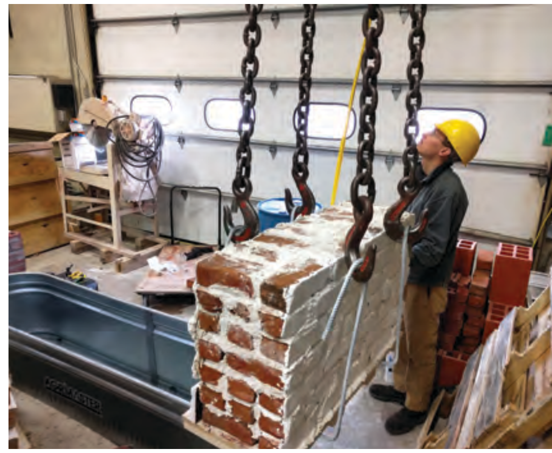

Fig. 3. Wall assemblies that were too heavy for two people to lift into and out of the immersion tank were hoisted by a crane. The wall assemblies were constructed on small wood platforms, and steel bars were used to create hooks with which to lift the samples. Courtesy of ERDC/CERL TR-19-8, 2019.

None of the interior wall finishes tested were classified by researchers as suitable for use below the BFE as a result of this test. Plaster walls displayed biological growth within wall cavities but not on the plaster surfaces. There were also visible cracks, some severe. The plaster results must be considered in the context of the short cure time and the movement of test samples; there is also the possibility that the substrate swelled, contributing to the cracking. It may be that binding agents dissolved in the water. Additional research is needed. The beadboard wainscot showed a tendency to warp and lengthened the drying time for a traditional masonry wall assembly.

Foam and mineral-wool insulation were also tested in this project. The foam

**Table 3. Wall Assemblies Sorted by the Number of Days Needed to Dry.**

*Note: The weight increase refers to the difference between the initial dry weight of the sample before inundation and the first recorded weight of the sample after the 72-hour simulated flood.*

| Wall sample | Percent weight increase | Days to final weight | Wall type |
|---|---|---|---|
| A | 8.6 | 15 | Eighteenth- to nineteenth-century brick, plaster interior |
| B | 2.7 | 19 | Late nineteenth- to early twentieth-century brick, structural clay tile, plaster interior |
| I | 10 | 19 | Eighteenth- to nineteenth-century brick with exterior limewash, plaster interior |
| C | 21.1 | 28 | Wood frame, no sheathing, wood clapboard, plaster on wood-lath interior |
| D | 23.6 | 28 | Wood frame with sheathing and Dutch lap siding, plaster on wood-lath interior |
| F | 25.3 | 28 | Wood frame, wood clapboard on sheathing, plaster on wire-lath interior |
| E | 6.3 | 29 | Eighteenth- to nineteenth-century brick with foam insulation, gypsum board interior |
| L | N/A | 29 | Wood frame, wood clapboard on sheathing, beadboard interior. *Note: Wall L does not have a recorded wet weight due to an equipment error with the scale.* |
| K | 15 | 31 | Wood frame, stucco on metal lath over sheathing, plaster on wire-lath interior |
| G | 25.6 | 31 | Wood frame, wood clapboard on sheathing covered by aluminum siding, plaster on wood-lath interior |
| H | 43.6 | 31 | Wood frame, wood clapboard on sheathing, mineral-wool insulation within cavity, plaster on wood-lath interior |
| J | 9.8 | 71 | Eighteenth- to nineteenth-century brick, beadboard interior. *Note: 71 days is artificially high due to a lapse in the ability to weigh Wall J while drying.* |

insulation proved to be a good host for biological activity, while the mineral-wool insulation absorbed and retained the most water. Mineral wool, while generally an inert material, contains starch binders that may contribute to the water retention. It was not possible to test other types of insulation that exist in some early wall assemblies. This could be addressed in future testing.

For the coatings that were tested—lead-based paint on vertical surfaces and shellac, tung oil, and floor wax on floors—there were some unforeseen outcomes. Surfaces covered with well-bonded lead-based paint performed well and seemed to resist biological growth consistent with known biocide properties, but there were some problems with paint flaking. This condition may have been the result of the wood swelling under the surface since the edges of the samples were not painted. On the floors, the shellac failed, becoming cloudy and discolored (Figs. 4–7).

## Using the Standard Test

As noted above, the original goal of this project was to provide results comparable to those of modern materials that are marketed as flood damage–resistant materials. However, in an attempt to replicate a real-world scenario as closely as possible—by testing materials in an actual assembly—it is possible that the test results did not provide comparable information. Modern flood damage–resistant materials may not have been tested in assembly, and the ratings reflect their isolation. *Technical Bulletin 2* cautions that the combination of acceptable structural and finish materials in assembly may not have the same classification as they would separately. *ASTM E3075* specifically allows tests "including, but not limited to: individual building materials and composite assemblies of building materials." *ASTM E3075* also notes that "the ability to directly compare test results will vary by many factors including test specimen size and whether test specimens are individual building materials or composite assemblies of building materials." Therefore, a second round of testing of the individual materials should be undertaken for the same materials used here in assembly before any comparisons are made to specific materials.

*ASTM E3075* is not explicit in all aspects of test design or the interpretation of the results. Specifically, there are no minimum or maximum test sample sizes recommended or provided. The standard does not establish how to treat materials that must be used as part of an assembly. For example, if siding is tested, should it be cleaned only on one side? Or, if tested in isolation, can it be cleaned on both sides even if this does not replicate real-world conditions? The standard requires a swab test for contamination from three surface locations, regardless of sample size and without guidance on selecting the three locations. One could argue that separate swab tests above and below the waterline are necessary, but this is not explicitly addressed in the standard. Are swabs required prior to immersion to give benchmark data? Should they be taken immediately after removal from the tank and again once the specimen is dry? Indoor environments harbor a variety of microorganisms or microbes. What are the normal levels seen prior to a flood event?[24] The lack of direction on these issues could lead to variation of testing results at different laboratories and across different studies.

Additionally, based on the provided rating scale and directives, the evaluation of the results is somewhat subjective. As previously noted, permanent staining is mentioned as problematic and a reason to rate a material in a lower category, but this does not affect performance. At the same time, the ASTM standard defines cosmetic damage as acceptable. When staining is considered cosmetic and when it is considered revealing of a larger underlying condition are unclear and could lead to high subjectivity in rating materials. Is there a distinction between the staining of materials that one would expect to refinish or repaint versus those that are not? There is also little information or guidance for interpreting the results of the swab analysis. Is there a threshold of acceptable contamination, or must anything other than a clean result automatically place a material in the unacceptable category? Is there allowance for introducing alternative cleaning products or methods that may treat a particular material or assembly more effectively? These are all concerns and considerations that warrant further discussion, review, and testing.

## Recommendations for Future Work

The NPS has already begun coordination with CERL to undertake a second round of testing following the *ASTM E3075* standard test procedure. This time, the test samples will not be wall and floor assemblies; instead, they will consist of the component materials of the sample assemblies from the first round of testing. Multiple samples of each material will be inundated in order to further confirm or adjust results. Material samples will be fabricated, where necessary, at the Historic Preservation Training Center in Frederick, Maryland, an office of the NPS, by tradespeople skilled in traditional methods and materials. Mortar, plaster, and stucco will be allowed to cure for at least 90 days. Humidity will be regulated. The testing is expected to be conducted throughout 2021. Results of the experiment will likely be available in 2022.

Additional testing could provide better recommendations for cleaning existing buildings after a flood and provide allowable alternatives rather than wholesale removal of finishes for historic buildings.[25] There are traditional building practices and materials in many cultures that provide water resistance or waterproofing. Testing the efficacy of such coatings and treatments might provide additional retrofit options for historic buildings. The success of a basic limewash in the first round of testing seems to be a positive sign for similar coatings. The NPS will continue to ex-

*Images arranged clockwise from Fig. 4 at upper right.*

Fig. 4. The exterior of Wall A was an example of an assembly that performed well in the immersion test. Note that there is some loss of the lime mortar on the surface. Courtesy of ERDC/CERL TR-19-8, 2019.

Fig. 5. The interior of Wall A. The painted baseboard harbored a high concentration of coliform bacteria. Plaster losses also occurred. Courtesy of ERDC/CERL TR-19-8, 2019.

Fig. 6. The exterior of Wall D, a wood-framed assembly. Note that the paint is flaking and cracking, allowing for the sewage surrogate to penetrate the wood siding. Courtesy of ERDC/CERL TR-19-8, 2019.

Fig. 7. The interior of Wall D, which had a three-coat plaster finish applied over reclaimed wood lath and a baseboard attached directly to the frame. Note the staining on the surface of the plaster. After immersion, bacteria and fungi can grow behind the baseboard and in the interior cavity behind the plaster wood lath. Courtesy of ERDC/CERL TR-19-8, 2019.

plore additional tests and studies as opportunities arise.

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## Notes

1. Jenifer Eggleston, Jennifer Parker, and Jennifer Wellock, *Guidelines on Flood Adaptation for Rehabilitating Historic Buildings* (Washington, D.C.: U.S. Dept. of the Interior, NPS, Nov. 2019), https://www.nps.gov/tps/standards/rehabilitation/flood-adaptation-guidelines.pdf.

2. Alan M. Foster, Gabriela M. Medero, Tom Morton, and Jim Buckman, "Traditional Cob Wall: Response to Flooding," *Structural Survey* 26, no. 4 (2008): 302–321. M. Escarameia, A. Karanxha, and A. Tagg, "Quantifying the Flood Resilience Properties of Walls in Typical UK Dwellings," *Building Services Engineering Research and Technology* 28, no. 3 (2007): 249–263.

3. A number of studies have been published by Historic England in their Research Report series that relate to water damage to historic buildings. While some discuss floodwaters, others discuss damage from water used in firefighting activity. These reports, while useful, do not simulate prolonged periods of flood. See *Technical Conservation Guidance and Research* (Historic England, Nov. 2020), https://historicengland.org.uk/content/docs/advice/technical-conservation-guidance-and-research-brochure-pdf/.

4. Heshmat Aglan, Robert Wendt, and Sherry Livengood, *Field Testing of Energy-Efficient Flood-Damage-Resistant Residential Envelope Systems Summary Report* (Oak Ridge, Tenn.: U.S. Dept. of Energy, Oak Ridge National Laboratory, June 2004).

5. Additional journal articles reviewed include Andrea B. Becker, William M. Johnstone, and Barbara J. Lence, "Wood Frame Building Response to Rapid-Onset Flooding," *Natural Hazards Review* 12, no. 2 (2011): 85–95; Ilan Kelman and Robin Spence, "A Limit Analysis of Unreinforced Masonry Failing under Flood Water Pressures," *Masonry International* 16, no. 2 (2003): 51–61; Ilan Kelman and Robin Spence, "An Overview of Flood Actions on Buildings," *Engineering Geology* 73, nos. 3–4 (2004): 297–309; Norberto C. Nadal, Raul E. Zapata, Ismael Pagan, Ricardo Lopez, and Jairo Agudelo, "Building Damage due to Riverine and Coastal Floods," *Journal of Water Resources Planning and Management* 136, no. 3 (2010): 327–336; and W. Roos, "Damage to Buildings," Dutch Government, Delft Cluster publication: DC1-233-9 (2003).

6. Escarameia, Karanxha, and Tagg, 249–263.

7. "Flood Plain Management Criteria for Flood-Areas," in *U.S. Code of Federal Regulations*, title 44, part 60.3 (Washington, D.C.: Dept. of Homeland Security, FEMA, 1976); see also part 9.4 for definitions. Base flood is defined as "the flood which has a one percent chance of being equaled or exceeded in any given year (also known as a 100-year flood). This term is used in the National Flood Insurance Program (NFIP) to indicate the minimum level of flooding to be used by a community in its floodplain management regulation." Substantial improvement is defined as follows, "any repair, reconstruction or other improvement of a structure or facility, which has been damaged in excess of, or the cost of which equals or exceeds, 50% of the market value of the structure or replacement cost of the facility."

8. *Technical Bulletin 2: Flood Damage–Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program* (Washington, D.C.: Dept. of Homeland Security, FEMA, Aug. 2008), https://www.fema.gov/media-library/assets/documents/2655.

9. *ASTM E3075-16: Standard Test Method for Water Immersion and Drying for Evaluation of Flood Damage Resistance* (West Conshohocken, Pa.: ASTM International, 2016), https://doi.org/10.1520/E3075-16.

10. Juan Nieves, Julia Moline, Michael House, Richard Walker, and John Ingargiola, "Flood Damage–Resistant Materials: Research and Evaluation," in *Building Walls Subject to Water Intrusion and Accumulation: Lessons from the Past and Recommendations for the Future*, ed. J. Erdly and P. Johnson (West Conshohocken, Pa.: ASTM International, 2014), 166–186.

11. *Technical Bulletin 2*, Table 2, pp. 7–11.

12. *Technical Bulletin 2* is referenced in the International Codes of 2009, 2012, 2015, and 2018. Additional flood-resistant design and construction standards from *Flood Resistant Design and Construction*, book set 24-14 (Reston, Va.: American Society of Civil Engineers, 2015)

are referenced in the 2015 International Building Code (IBC) and the 2015 International Residential Code (IRC).

13. *Technical Bulletin 2*.

14. Suzana Radivojevic, "Wood Species Identification Report," report for Ligno Logic, LLC, Dec. 31, 2020.

15. Radivojevic.

16. The sewage surrogate was *Escherichia coli*. Mold surrogates were *Penicillium brevicompactum*, *Aureobasidium pullulans*, and *Eurotium herbariorum*.

17. Another future study could look at the effects of different drying regimes.

18. Bricks will not suffer in the test period but may be affected, not by the waters, but by the cryptofluorescence thereafter as salt crystalizes behind the face or due to pollutants and damage to substrates.

19. *ASTM D7789-12: Standard Practice for Collection of Fungal Material from Surfaces by Swab* (West Conshohocken, Pa.: ASTM International, 2012), https://doi.org/10.1520/D7789-12.

20. The laboratory report for this project, including specific weight measurements and swab analysis, is available in Peter B. Stynoski, Thomas A. Carlson, Abigail M. Brake, Clint M. Arnett, Marion L. Banko, and Matthew M. Landi, *Flood Resilience of Traditional Building Materials: Report of Simulated Flood Immersion According to ASTM E3075 Standard Procedures* (Champaign, Ill.: U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, May 2019), https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/32823/1/ERDC-CERL%20TR-19-8.pdf.

21. Robert C. Mack and John P. Speweik, *Preservation Brief 2: Repointing Mortar Joints in Historic Masonry Buildings* (Washington, D.C.: U.S. Dept. of the Interior, NPS, Oct. 1998).

22. Stynoski et al.

23. Michael Henry and Tina Therrien, *Essential Natural Plasters: A Guide to Materials, Recipes, and Use* (Gabriola Island, British Columbia: New Society Publishers, 2018).

24. *ANSI/IICRC S500/2015: Standards and Reference Guide for Professional Water Damage Restoration*, 4th ed. (Las Vegas, Nev.: ANSI/IICRC, 2015); see chapter 2, "Microbiology of Water Damage," and chapter 17, "Materials and Assemblies."

25. There is a paucity of citations from Canadian and European authorities on flooding behavior and drying of historic materials; Historic England publishes several credible sources such as *Flooding and Historic Buildings* (April 2015); *A Preliminary Study of Flood Remediation in Hebden Bridge and Appleby* (2017); *Health Risks from Contaminated Floor Water in the UK* (2017); *Does Plaster Retard the Drying of Walls after Flooding*? (2018); and *Analysis of Drying Data from a Medieval Hall after Flooding* (2017).

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