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Experimental Investigation of Material Flood Damage to Support Multi-Scale Flood Damage Prediction

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EXPERIMENTAL INVESTIGATION OF MATERIAL FLOOD DAMAGE TO SUPPORT MULTI-SCALE FLOOD DAMAGE PREDICTION

by

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ABSTRACT

Current practice of flood loss prediction presents limitations in accurately predicting building flood losses at multiple scales. While whole-building estimates can more accurately predict high-level losses (i.e., large groups of buildings), a significant analysis error is revealed with small-scale (i.e., individual, or small groups of buildings) investigation. This research presents a robust, data driven, building damage model seeking to elucidate a more fundamental understanding of flood damage of material components commonly used in residential construction. The framework of the model is based on a component-level damage database composed of data collected from experimental analysis. Structures with standard residential construction materials were built and incrementally flooded for short periods of time. The materials were assessed to determine the level of damage inflicted by the simulated flood events and catalogued based on material restorability. The restorability was determined through indicators such as moisture intrusion, corrosion, and mold contamination. The framework for the flood loss prediction model will be designed to incorporate damage uncertainty and be capable of analysis at multiple scales. This study not only provides a fundamental understanding of material damage, but also develops a more effective modeling tool of building community resilience through flood risk analysis and hazard mitigation planning.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Hazard mitigation is becoming a priority for many communities as natural hazards, and more specifically floods, are becoming more destructive every year. However, the financial burden of protection for communities is based on accepted but potentially antiquated methods. While the cost of materials fluctuates, the cost estimations of damage tend to be observed as over and underestimates. These assessments of either potential or existing flood damage are done utilizing depth-damage curves. These curves are developed based on historical data or on expert opinion. There is great uncertainty in existing models and methods that could potentially be resolved by conducting experimental analysis on construction materials. By finding the more precise damage inflicted by flood events, benefit-cost analysis could be efficiently conducted, providing more educated opportunities for communities to prepare their hazard mitigation plans.

1.2 Research Needs

Risk mitigation practices are frequently being found ineffective and too generic of estimations for flood loss assessment (Xian, Lin, & Kunreuther, 2017), (Aerts, Lin, Botzen, Emanuel, & de Moel, 2013), (McGrath, Kotsollaris, Stefanakis, & Nastev, 2019).

There is very little exploration done into the experimental collection and review of material reactivity during and after flooding scenarios. The data that has been studied and collected, however, is disconnected from the monetary assessment that is increasingly important in risk mitigation planning. Recent research has only been working to disprove the effectiveness of current standards and systems (Xian, Lin, & Kunreuther, 2017). Further flood damage investigations utilizing software also generate outputs based on basic independent variables such as house size and elevation (McGrath, Kotsollaris, Stefanakis, & Nastev, 2019). The standardized experimental collection of damaged material data, combined with cost-benefit analysis, would introduce a new and robust perspective for the analysis of flood hazards.

A new, efficient method of calculating cost estimations following a flood event will allow for better practice in reporting losses for funding in the future. Another key component that is not generally available when conducting loss assessments is the accessibility to residents and homeowners who want to assess their own homes.

This research looks to analyze the effects and reparability or salvageability of building materials following disastrous flooding events. The collected material damage data will be used to develop a database for future reference of post-natural disaster residential building investigations. A model will provide a method of quantifying the amount and types of material that can be salvaged, or if they need to be considered compromised and discarded. This data will then be converted into a monetary value utilizing current material-cost relationships.

1.3 Research Objectives

The objectives of this research project are to begin the process of collecting experimentally derived flood damage data. This will be done and assessed by the three objectives that are outlined.

1.3.1 Objective 1: Assess the Material Integrity

The first objective is to create built structures with residential building materials commonly used in Louisiana and other parts of the United States. These materials will be tested at varying flood depths throughout a short term, less than 48 hours, flood test. The materials will be assessed both during and after the flood tests to determine their integrity. The data will be collected as percent moisture within the material that can then be utilized to determine damage. Full evaluations of the materials will determine if they have reached the end of their useful life or if they can be restored and reused.

1.3.2 Objective 2: Quantify the Material Damage

The second objective is to quantify the material damage in a way that can then be converted into monetary values. The percent moisture values will be processed to determine the percent damage of a whole wall assembly. The percent damages at varying flood depths can then be utilized to develop depth-damage curves.

1.3.3 Objective 3: Develop a Material Database

The final objective is to create a database that can be populated with raw percent moisture damage to then create depth-damage curves for a wide variation of construction materials. These depth-damage curves will be for material components which in the future can then be integrated for full structure analysis.

1.4 Thesis Organization

This thesis is organized into six chapters: (1) Introduction, (2) Literature Review, (3) Data Collection, (4) Data Analysis and Results, (5) Interpretation of Results, and (6) Conclusions and Future Work. Chapter 2 reviews the relevant literature pertaining to flood loss assessments, depth-damage curve generation, and benefit-cost analysis. Chapter 3 explains the entire data collection process. It starts with describing the construction procedure and discussing each material and its appropriate combination within the structure. Each flood test is outlined, both freshwater and saltwater, and includes the restoration period in between the two tests. Chapter 4 discusses the data analysis process that was followed to organize the data. The percent moisture values are converted into percent damage that can then be plotted to create depth-damage curves. Chapter 5 compares the newly created depth-damage curves to current curves used in common practice in Louisiana. This step serves to validate whether variability exists between the newly created curves, and those that already exist. Chapter 6 presents some conclusions from the data analysis and research presented in this thesis. This topic requires further research and therefore this chapter also discusses the opportunities for future work on expanding the database, developing a multi-scale model, and applications to test the accuracy of a model.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the United States, flooding is one of the greatest natural hazards costing billions of dollars in property losses each year (NOAA, 2020). Historical and predicted data indicate that the frequency and intensity of flooding events will only increase year after year (NOAA, 2020).

Following a natural disaster, the costs of material repairs increase drastically (Khodahemmati & Shahandashti, 2020). The rapid material shortage following a natural disaster is known as a demand surge and can cause material costs to increase from 10%-40% as seen after Hurricane Katrina (Khodahemmati & Shahandashti, 2020). While the cost inflation is inevitable as witnessed by any typical demand increase, the number of materials required can be refined to further optimize the financial estimations of damages.

One of the best practices for protecting communities from continued damage and losses following a natural disaster is hazard mitigation. Utilizing mitigation planning methods provides solutions that would encourage long-term protection as opposed to a continued cycle of damage and reconstruction after every disaster (FEMA, 2022). These resiliency projects can include drainage, adapting building elevations, and floodproofing. In Louisiana, specifically, communities are required to have mitigation plans to be able to qualify for grant funding following a disaster. One source of grant funding is through the Federal Emergency Management Agency (FEMA) Hazard Mitigation Grant Program (HMGP). These projects are typically analyzed utilizing cost-benefit analysis; they are deemed cost-effective when the future benefits of risk reduction, such as losses to life and property, exceed the actual cost of the project (FEMA, 2020). Developing cost estimates typically yields results that are over and underestimations, leaving large ranges of uncertainty for these estimations (Freni, La Loggia, & Nortaro, 2010). Most methods for observing damage assessments and data collection are based on large-scale sets of data (de Moel, et al., 2015). There is a need for a small-scale approach to collecting detailed loss data with the hopes of improving damage estimates (Schröter, et al., 2014), (Ernst, et al., 2010), (Apel, Aronica, Kreibich, & Thieken, 2008).

Another risk assessment program that is internationally accepted, HAZUS, was developed by FEMA. This program was created for use by floodplain managers, stating that experience in ESRI's ArcGIS software is necessary for user performance (Scawthorn, et al., 2006). The HAZUS program creates hazard and loss estimations using depth-damage curves. Depth-damage curves, like cost-benefit analysis estimations, leave plenty of room for uncertainty as they rely on generalized historical-based data or professional engineering judgment.

There has been an increase in risk mitigation efforts to diminish the effect of floods and the costs that come along with the damages (FEMA, 2020). The principal area of uncertainty regarding these efforts lies within the model inputs and outputs. Studies are looking into these models (Scawthorn, et al., 2006) but not thoroughly enough into the precision of their processes (Wing, Pinter, Bates, & Kousky, 2020) (Schröter, et al.,

2014) (de Moel, et al., 2015) (Ernst, et al., 2010) (Apel, Aronica, Kreibich, & Thieken, 2008).

2.2 Functions

When developing cost estimation models, whether they be benefit-cost analyses for risk mitigation projects or calculating expected damages from floods for flood risk analysis, a Catalog of Residential Depth-Damage Functions (Davis & Skaggs, 1992), such as the one created by the US Army Corps of Engineers, is utilized. A depth-damage function is commonly employed when assessing building damage due to flooding. These functions, derived from surveys of 1960-1995, are functions of percent damage with respect to inundation depth (Davis & Skaggs, 1992). However, other functions relay either absolute or relative damage against water depth, flood duration, building type, contamination, or building age (Merz, Kreibich, Schwarze, & Thieken, 2010).

The HAZUS Flood Model, created by FEMA, can calculate hazard and loss estimations of flood events, by utilizing more than 900 depth-damage curves for various structures, facilities, and contents (Scawthorn, et al., 2006). These depth-damage curves are pulled from a variety of sources including the Federal Insurance and Mitigation Administration (FIMA formerly FIA) (FEMA, 2003). The curves utilized from the FIA, as shown in **Figure 2-1** have gone through a process of being “credibility weighted” to estimate the flood damage. These credibility weighted curves are adjusted to remove items that are not covered by insurance such as basement flooring and other finishes. The US Army Corps of Engineers (USACE) and USACE Institute for Water Resources (USACE IWR) also contributed depth- damage curves, such as those from the Chicago, Galveston, New Orleans, New York, Philadelphia, St. Paul, and Wilmington Districts, that are utilized within the HAZUS model (FEMA, 2003).

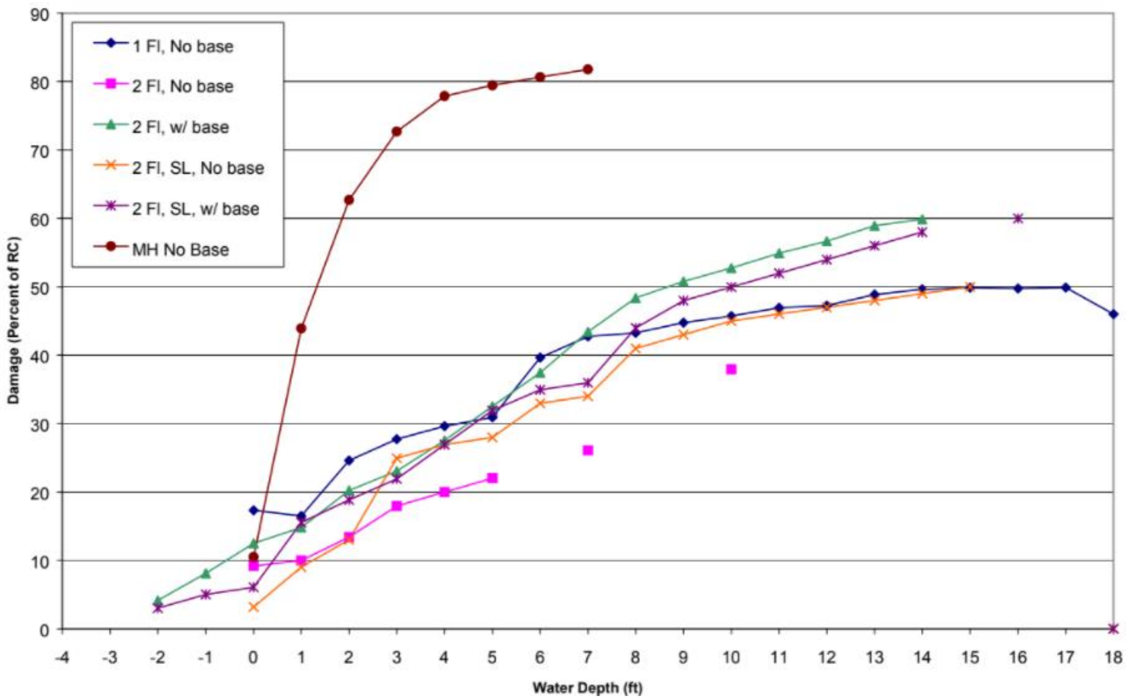

Figure 2-1: Federal Insurance Mitigation Administration Credibility-Weighted Building Damage Curves (12/31/1998) (FEMA, 2003)

The residential depth-damage functions only utilize basic structural classifications as shown in **Table 2-1** from FEMA's Benefit-Cost Analysis Reference Guide (FEMA, 2020).

Table 2-1: Default Residential Depth-damage Functions (FEMA, 2020)

Mobile Home
One-Story with Basement
Split-Level with Basement
Two or More Stories with Basement
One-Story without Basement
Split-level without Basement
Two or More Stories without Basement

Initial use of the depth-damage guide begins with the understanding and identification of the contents, structure, and outside property that have been affected by immersion (Davis & Skaggs, 1992). The guide, however, does not delve into any damage that could occur above the level of immersion. This leaves out any damage that may occur due to the cohesive and adhesive properties of water during absorption into materials.

The depth-damage functions are created based on synthetic analysis, historical analysis, and adaptations from currently existing damage functions specific to a certain locality (Davis & Skaggs, 1992). The historical analysis method employs past flooding events and the data taken to develop future estimates for determining potential damage and cost assessments. Synthetic analysis adapts data that may be out of date or unavailable and uses hypothetical damages and engineering judgment to develop estimates (Xian, Lin, & Kunreuther, 2017).

2.2.1 Historical Analysis

The most common method for creating depth-damage functions and cost estimates is through historical analysis. This empirical historical analysis has been argued to be more accurate than synthetic analysis (Pistrika, Tsakiris, & Nalbantis, 2014). This is due, in part, to the use of actual data and not theorized damage. These damage assessments typically quantify and reflect damage mitigation measures that can be translated into the modeling (Merz, Kreibich, Schwarze, & Thieken, 2010). Some examples of historically derived depth-damage curves are those from the US Army Corps of Engineers (FEMA, 2003). The USACE Galveston District, for example, utilized post-event surveys and flood damage records. They are even utilized by other Districts such as Tulsa and Fort Worth. The HAZUS Flood Model has three levels of analysis that become more advanced as the input data is more refined as illustrated by **Figure 2-2**. However, they are based on historical data which presents its own shortcomings (FEMA, 2020).

Damage surveys are conducted after flood events and, generally, they are not detailed due to the effort and specificity needed per location. These data sets also require extrapolation to interpret results outside of the range of actual flood depth. Another downfall for using historical data is that it is site-specific and may not universally encapsulate damages in different geographic locations (Smith, 1994). Because there are varying differences in warning time, flood experience, and a wide variety of building materials, the transferability across geographic locations is extremely difficult and lacks accuracy (Smith, 1994).

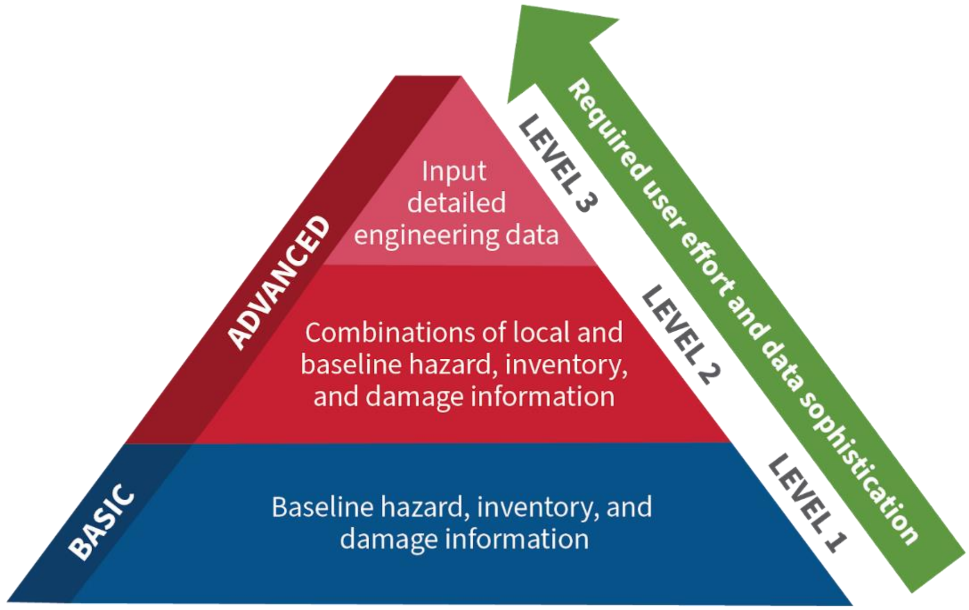

Figure 2-2: HAZUS Risk Analysis Levels (FEMA, 2020)

2.2.2 Synthetic Analysis

After realizing some gaps in data from using historical analysis, White (1945) coined the term and method of "synthetic analysis." The use of synthetic analysis stems from utilizing professional engineering observation and hypothetical analysis (White, 1945). The New Orleans District of the US Army Corps of Engineers (USACE) uses depth-damage functions derived from expert opinion (FEMA, 2003) (US Army Corps of Engineers, 2004). These synthetic curves were created by Gulf Engineers & Consultants (GEC) who sought out eight professional opinions from knowledgeable experts in the Louisiana area. Because synthetic analysis does not rely on actual flood events, the data can be applied to any location with relative ease (Smith, 1994) and damage information for a wide range of flood depths can be created (Merz, Kreibich, Schwarze, & Thieken, 2010). A comparison of the GEC and USACE Depth-damage curves for residential structures is shown in **Figure 2-3**.

There is also the underlying subjectivity of synthetic analyses that results in uncertain damage assessments (Merz, Kreibich, Schwarze, & Thieken, 2010). Another drawback to synthetic analysis is that potential mitigation actions are not reflected (Merz, Kreibich, Schwarze, & Thieken, 2010).

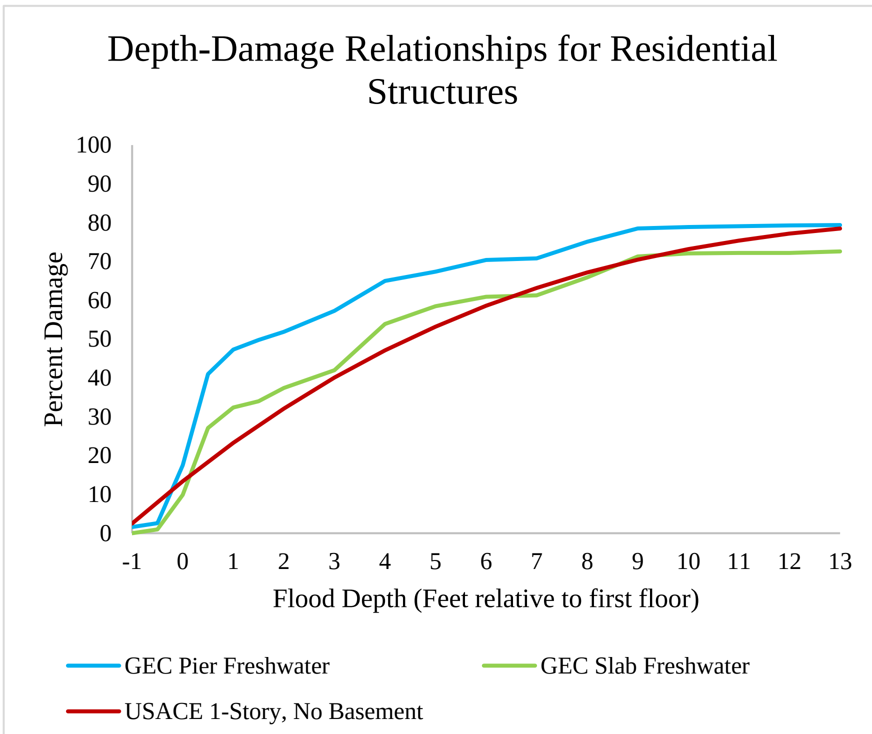

Figure 2-3: Depth-Damage Relationships for Residential Structures

While both historical and synthetic analyses have their drawbacks, the US Army Corps of Engineers, Australia, and Germany have done work to combine the two methods (Merz, Kreibich, Schwarze, & Thieken, 2010). In some instances, they supplemented the historical data with synthetic analysis; in other cases, they have evaluated the synthetic models with empirical data to provide some support for the method (Merz, Kreibich, Schwarze, & Thieken, 2010). Case studies in northern Italy have also been evaluated with both synthetic and historical damage models but again, only basic inputs were utilized to observe damage and loss (Amadio, et al., 2019).

2.3 Uncertainty

While there are continued efforts to improve the precision and accuracy of flood damage models, a large window of uncertainty remains (Aglan, Wendt, & Livengood, 2005) (Coastal Protection and Restoration Authority of Louisiana, 2017) (McGrath, Abo El Ezz, & Nastev, 2019) (Merz, Kreibich, Thieken, & Schmidtke, 2004) (Wing, Pinter, Bates, & Kousky, 2020) (Wurbs, Toneatti, & Sherwin, 2010). The data sets, although available, are scarce, generally incomplete, and quite difficult to compare amongst each other (Merz, Kreibich, Thieken, & Schmidtke, 2004). This uncertainty in data translates into the depth-damage curves and further into the cost estimates. A study done in the Netherlands (Wind, Nierop, de Blois, & de Kok, 1999) comparing two floods in two different years of the same area found that a percentage of the uncertainty of 20-40% was attributed to missing actual reported damage or over-reported damage. This brings up the need for a uniform assessment to be utilized across the board for every residential or commercial building affected. Lack of consideration for uncertainty and error in analysis can lead to inefficient mitigation practice which potentially yields unfeasible or ineffective funding of mitigation projects. Inefficient spending of FEMA has also been brought to a congressional hearing with the effort to better the management and practices of FEMA following natural disasters (Majority Staff of the Senate Subcommittee on Emergency Management, Intergovernmental Relations, and the District of Columbia, 2014).

Based on previous research, the uncertainty varies with respect to the spatial scale, and error in loss estimates can be greater at smaller scales compared to larger spatial scales (Pistrika & Jonkman, 2010). The flood damage data needs to be collected at a variety of spatial scales: micro, meso, and macro-scale. The spatial scales will allow for relationships between the flood characteristics and the amount of damage to be formed and analyzed (Merz, Kreibich, Thieken, & Schmidtke, 2004). At macro-scale evaluations, meaning on a national level, global areas of risk can be identified (de Moel, et al., 2015). At smaller scales (meso, micro), more detailed evaluations of regional and local assessments can be utilized for effective flood loss prediction (de Moel, et al., 2015) (Pistrika & Jonkman, 2010). Analyses have been done on separate spatial scales, but no models have been created that can perform flood loss assessments across multiple scales. The ability to have a singular model based on detailed material damage data will present the opportunity to assess the damage on varying scales.

Some studies have worked to provide residents the opportunity to evaluate their losses at a more comprehensive analysis of the damage. However, these are very generic and only allow for very basic inputs to calculate outputs. Another important aspect to note is the value of consumer goods that are being replaced following a flood event. According to Merz (2010), it is recommended that the depreciated value of goods be utilized in loss estimates as opposed to new full replacement costs. By utilizing new replacement costs, the loss estimates are overestimated as to what is actually lost during the flood event (Merz, Kreibich, Schwarze, & Thieken, 2010). Overall, depth-damage analyses provide inaccurate estimates as they greatly overgeneralize the damage and cost assessments (FEMA, 2020), (Davis & Skaggs, 1992), (Wind, Nierop, de Blois, & de Kok, 1999).

It has been concluded by Schröter (2014) that more complex models with higher variable counts yield more precise loss estimations. These models however still maintain a significant amount of uncertainty as the analyses fail to incorporate and understand the extent of material damages (Schröter, et al., 2014). A large gap in understanding the material responses due to flooding exists and this is where the models fail to relay accurate loss estimations. The results of current models yield uncertainties up to a magnitude of a factor of 5 (Wagenaar, de Bruijn, Bouwer, & de Moel, 2016). As natural hazards occur more frequently and more intensely, these assessments need to yield results with higher accuracy to optimize the funding potential.

2.4 Experimental Analysis

Depth-damage functions, developed by historical and synthetic analyses, have revealed the gap in fully understanding the damage and loss following a flood event. Experimental analysis could potentially resolve some of the concerns that are associated with synthetic and historical analysis such as uncertainty. By breaking down the structures to a component material level, one could assemble a structure to their own specifications without having to rely on convenient comparisons which would be the case for using existing damage models. Assessing the damage at a component level could then translate into larger spatial scales and they can then be easily compared amongst each other. Experimental analyses have been conducted with regard to flood data but only for the observation of flow intrusion into buildings (Mignot, Camusson, & Riviere, 2020), (Fukuoka & Kawashima, 1996). There has also been research done that inspects the material reactivity but not to the extent of associating damage with costs (Aglan, et al., 2014).There have yet to be any flood loss prediction models that are based on experimentally derived material damage. This research will create a component level damage database that accurately describes the damage inflicted on the materials that can then be integrated to support analyses on varying spatial scales. By creating a database of material damage in a controlled setting, the data could be quantified and converted into monetary assessments.

CHAPTER 3

EXPERIMENTAL SETUP AND DATA COLLECTION METHODOLOGY

3.1 Introduction

This chapter will walk through the experimental setup and how the data was collected throughout the flood tests. The construction of the structure is detailed followed by the process of flooding, restoring, and flooding the structure again. The data collection includes the testing of multiple material combinations for two flood scenarios. Residential construction follows typical codes and standards for materials such as the International Residential Code. These standards were maintained during the experimental setup of the smaller scale, 8ft x 8ft structures. Multiple material combinations were tested to lay the foundation for the development of a large database of damage values and to capture variation across multiple material combinations. Building a comprehensive database is critical to the creation of a more robust approach to modeling building loss across multiple scales. Different floodwater conditions were also tested to introduce damage incurred from storm surge flooding. It must be noted that only inundation flooding was tested; wave action and velocity were not within the scope of the flood testing. However, saltwater and freshwater were both utilized during different experimental flooding events. Following each flood test, materials were carefully removed and observed. In an attempt to reduce costs during reconstruction, as many materials as possible were salvaged.

3.2 Construction Materials

A variety of construction materials were used when constructing and reconstructing the structure. There were two flood tests, a saltwater, and a freshwater flood test. While there were two different flood tests, the same structural frame was used both times. The materials for both tests were kept, for the most part, identical even after testing and restoration. The material combinations are outlined below in **Table 3-1**.

Table 3-1: Material Combinations for Both Freshwater and Saltwater Tested Structures

	Structure	***Insulation***	***Exterior Finishes***	***Interior Finishes***
Wall 1	Wood-frame	Fiberglass Batt	Fiber-cement Siding	Paper Gypsum
Wall 2	Wood-frame	Fiberglass Batt	Vinyl Siding	Paper Gypsum
Wall 3	Wood-frame	Foam Board	Vinyl Siding	Paper Gypsum
Wall 4	Wood-frame	Foam Board	Fiber-cement Siding	Paper Gypsum
Floor 1	Concrete Slab	-	-	Engineered Wood
Floor 2	Concrete Slab	-	-	Vinyl Tile
Floor 3	Concrete Slab	-	-	Ceramic Tile
Floor 4	Wood-frame	-	-	Engineered Wood
Floor 5	Wood-frame	-	-	Vinyl Tile
Floor 6	Wood-frame	-	-	Ceramic Tile

3.2.1 Structure

The wall framing of the structure was built with wood 2”x4” studs. The foundation was split in half to allow the opportunity to test two different types of residential foundations. A 6-inch reinforced concrete slab was installed on one half, with self-leveling underlayment to ensure a level surface. The other half was a wood frame foundation with a ½” OSB piece affixed on top for a level subfloor. A door and window were installed on two of the walls to include typical residential features.

3.2.2 Insulation

The insulation was installed to maximize the material combinations as well. The R-13 3-½” thick fiberglass batt was installed on walls with different foundation types to encompass the effects of the concrete and wood foundations when flooded. The R-6.65 1” foam board was installed in three layers and on the different foundation types.

3.2.3 Exterior Finishes

The exterior wall finishes were each installed on half of the structures’ walls. The fiber cement siding was installed on two walls with different foundations and insulation types. The vinyl siding was also installed with two different types of foundations and insulation types. By incorporating these variations, the structure was able to encompass six different material combinations.

3.2.4 Interior Finishes

All the interior walls were finished with ½” paper-faced gypsum panels that were then painted with two coats of interior latex paint. The flooring was installed based on proper installation techniques for each flooring type. The ceramic tile, vinyl tile, and engineered hardwood were installed on a section of each subfloor. Therefore, a total of six flooring combinations were utilized.

3.3 Construction Methods

3.3.1 Initial Construction

The first thing that was constructed was the 18ft diameter above-ground swimming pool. The pool was installed within an 18’x20’ soil box in the Trenchless Technology Research Center at Louisiana Tech University’s South Campus.

The foundation had to be installed within the swimming pool. Two types of foundations were installed together to allow testing of two different types of residential foundations. A 6-inch reinforced concrete slab was poured to create 4’x8’ of the structures’ foundation. A self-leveling underlayment was installed on top of the concrete foundation to ensure a level surface for further construction. The other 4’x8’ section of the foundation was a wood frame foundation with oriented strand board (OSB) affixed on top for a level subfloor. The foundation assembly is shown in **Figure 3-1**.

Figure 3-1: Foundation Drawing

The wall framing of the structure was wood-stud spaced 16” center-to-center. A 3’x6’8” standard door and respective doorway were installed on Wall 1 and a 3’x5’6” window was installed on Wall 3 as shown in **Figure 3-2**.

Figure 3-2: Structural Framing Drawings

On the exterior side of the structure, ½" OSB was installed as the exterior sheathing. Following the OSB, the Rex Wrap ESR-1602 Weather Resistant Barrier was nailed down and then the different types of siding were installed. The fiber cement siding was installed on Wall 1 and Wall 4 using an air-compressed nail gun. The vinyl siding on Wall 2 and Wall 3 was installed using a hammer and nails while clipping the panels into each other as they were installed upward from the bottom. The door frame itself was made from wood 2"x4" studs with the door itself being a 6-panel hollow core primed composite interior door. The window was also framed with wood 2"x4" studs. After the window casing was installed, all framing joints were caulked for extra protection. **Figure 3-3** shows the exterior finishes of the structure as well.

Figure 3-3: Exterior Finishes Drawings

The insulation was then installed on the interior of the walls. The fiberglass batt was installed by pressing them into the space between the studs from the top of the wall to the baseplate at the bottom. The foam board was installed on its two walls by cutting the foam panels to fit in between the studs. Three layers of foam board were used, and small pieces were cut to fit around smaller areas such as the space between the floor and window. The insulation can be seen in **Figure 3-4** where the white sections represent the foam board, and the pink represents the fiberglass batt insulation.

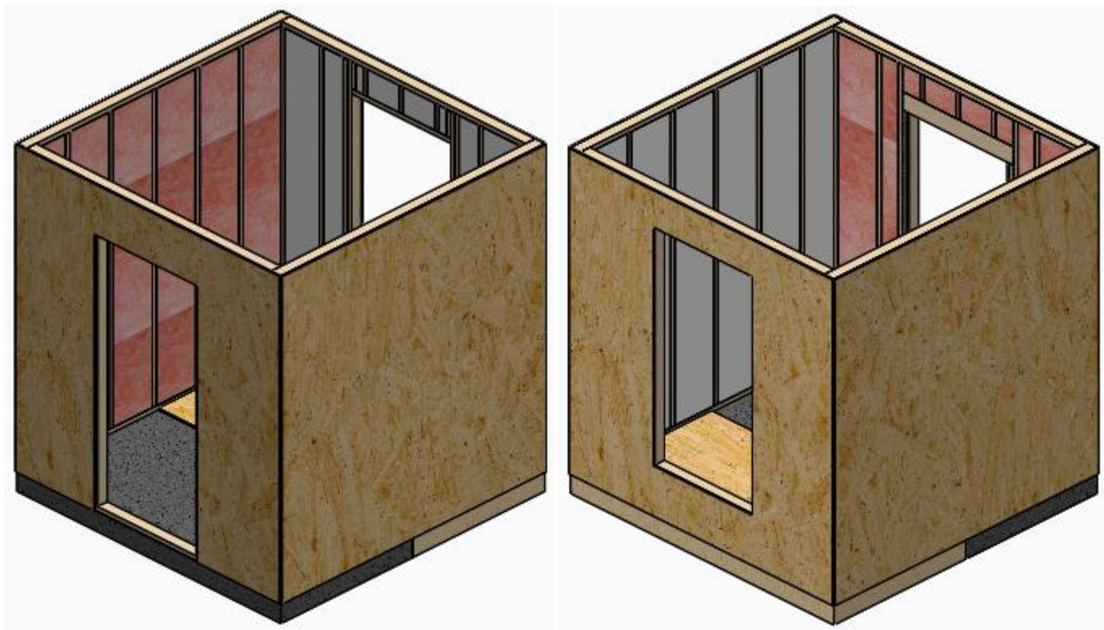

Figure 3-4: Insulation Drawings

The interior walls were then finished with paper-faced gypsum panels. The panels were cut to fit and then taped and filled with a drywall joint compound. Once the joint compound had dried and set, two coats of interior paint were applied to the walls.

The flooring was installed based on proper installation techniques for each flooring type. Under the ceramic tile section on the wood subfloor, a ⅜” cement board was installed per standard construction practice. The 16”x16” ceramic tiles were then installed on top of the cement board with mortar and finished with grout. The 12”x12” vinyl tiles were applied with an adhesive although there was already some adhesive on the backside of the tiles. The existing adhesive proved to be insufficient for properly bonding the tiles to the subfloor. The 3” wide engineered hardwood was applied on the wood subfloor with a compressed air nail gun. On the concrete foundation, adhesive was used to ensure the engineered hardwood would be secured to the subfloor. The flooring was installed to allow for 6 different combinations of flooring and subflooring as can be seen in **Figure 3-5**.

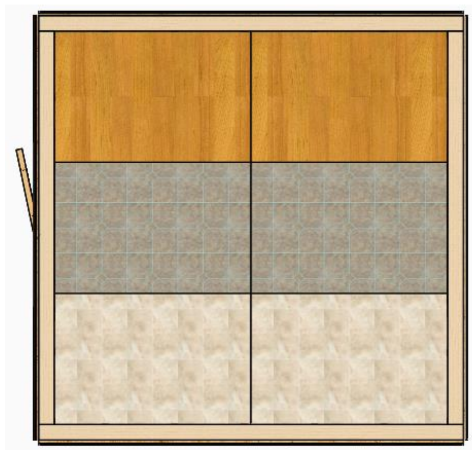

Figure 3-5: Flooring Drawing

Following the completion of the flooring, 3-½” wide baseboards, as well as trim around the door and window, were installed and caulked. The internal finishes can be seen in **Figure 3-6** with the paper gypsum paneling and the baseboards around the edge of the flooring. Final section views of the structure can be seen in **Figure 3-7**.

Figure 3-6: Internal Finishes Drawings

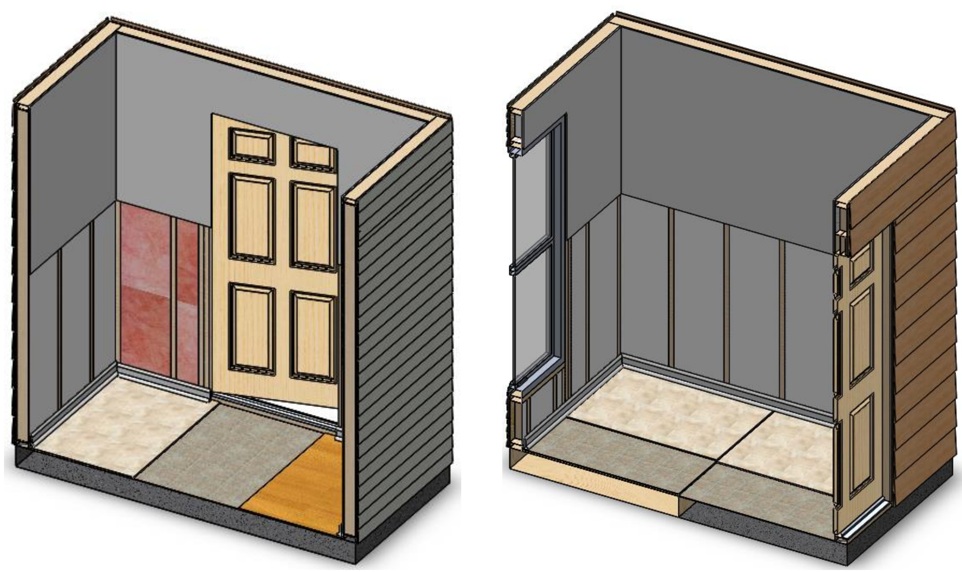

Figure 3-7: Section Views of the Finished Structure

During construction, the swimming pool liner acquired scratches, cuts, and holes. In an effort to mitigate leaking of the pool into the soil box during flooding, two coats of liquid rubber coating were applied to the bottom and one foot up the sides of the swimming pool.

3.4 Flood Testing

3.4.1 Freshwater Flood Test

After the first structure was completed, the first flood test could be performed. Lines were drawn on the walls inside the house to mark every 6 inches in height where measurements would be taken. For materials where the pin probe would not easily pierce or reach materials deep within the wall, a drill was utilized to create ⅛" diameter holes for moisture measurements.

Baseline measurements were taken with a Protimeter Surveymaster Moisture Meter. This instrument uses electrical conductance principles to measure the moisture level of a material in between the two electrodes. When the instrument is used in wood, the readings are actual percent moisture content readings; when the instrument is used in materials other than wood, then a percent wood moisture equivalent is read. The measurements were taken at multiple locations on each wall and floor, both inside and outside of the structure. The weather was also recorded for future reference, as the humidity in the area fluctuates frequently. A timer was started, and the pool was then filled with the first 3 inches of water. Utilizing three garden hoses at once allowed for the three inches to be achieved in approximately 30 minutes. The hoses were then turned off, while the timer kept going to a 2-hour mark. A little bit before the 2-hour reading, measurements with the moisture meter were taken at every possible location that was predetermined. This ensured that at the 2-hour mark, the water could be turned on again without disrupting the readings that would potentially be covered up. Extra care was taken to not splash water or force water onto the structure, as flow velocity or flood waves were not part of the intended scope of these flood tests. The moisture meter would read any moisture measurement above 20% as “Wet.” However, to avoid damage to the moisture meter, any measurement location that became fully submerged was marked as 99.9% moisture. The process of filling the pool, letting it soak, and taking measurements every two hours continued until a maximum water level of 36 inches was reached.

After taking the reading at 36 inches, the pool was drained using a Honda WB30XT General Purpose Water Pump with an inlet and outlet of 3 inches and a flow rate of 290gpm. Buckets and a wet vacuum helped to remove the last ½ inch of water that the pump could not obtain. The structure was then left overnight and 24 hours later, material deconstruction took place.

3.4.2 Restoration

Following the flood test, materials were carefully removed for inspection. They were closely examined for damage, mold, or other indications that would potentially render them irreparable. While the goal was to restore as many materials as possible, some materials were immediately disposed of.

The deconstruction began by removing the baseboards followed by the soggy and damaged paper-faced gypsum paneling with a gooseneck wrecking bar. After removing this first layer, the insulation could then be examined to determine its state. If the material integrity was deemed irreparable, then the material was discarded. The materials that could be restored were strategically laid out to dry with proper air circulation. Removing these wall components would allow ventilation for the OSB sheathing to dry out.

Once the walls were deconstructed, the flooring was assessed and then removed. Some flooring types were only able to be removed by destroying them. This deemed them irreparable, especially since potentially leaving them intact would create the potential for mold to grow underneath. Other flooring types were able to be pulled up and set aside to dry. By removing the flooring, the subfloor could then be aired out with the intention of preservation.

After removing as many materials as possible, the structure would then be left to air out with two fans on for increased ventilation. After 3 months, the OSB sheathing, studs, and foundations were checked with the Protimeter Surveymaster Moisture Meter to ensure they read as “Dry” before reconstruction would take place. The reconstruction period took about 4 weeks, and the structure was then ready for the second flood test.

A 1-gang plastic outlet box was installed on wall 4 against one of the studs. A 15-Amp electrical outlet was installed within the box and 12/2 solid non-metallic sheathed wiring extended to the top of the wall. After the foam boards fully dried out, they were reused and installed, keeping the new electrical box in mind and making adjustments. New fiberglass batt insulation was installed in only the removed sections, followed by the placement of new paper gypsum panels. The walls were taped, filled with a drywall joint compound, and painted.

New flooring had to be utilized, as a majority of the flooring was irreparable following the flood test. The salvaged baseboards and trim were sanded down and repainted. They were properly installed again with little to no variation from their original installation. The rubber coating on the bottom of the pool was not able to withstand the draining process and therefore needed to be resealed. Two new coats of liquid rubber coating were applied in preparation for the second flood test. The structure and its enclosure were fully reconstructed and ready for the second flood test.

3.4.3 Saltwater Flood Test

After the freshwater test, it was determined that the data collection methods needed to be altered to achieve improved precision, ideal for analysis. Instead of taking measurements every 6 inches, the goal was to test approximately every 1-2 inches. The measurement holes for the long probes were preset, but not measured and spaced out exactly.

The Protimeter Surveymaster Moisture Meter was again utilized to take all moisture readings. The baseline measurements were taken, and the weather conditions were recorded. To achieve a salt content of 3500ppm, 9 pounds of 100% Sodium Chloride Clorox Pool Salt was added per every 2 inches of tap water. Water was filled into the pool using 3 garden hoses. Once the pool had filled 2 inches, the 9 lbs. of salt were added and then mixed in gently so as not to create any splashing onto the structure. The saltwater was then left to soak for 2 hours. About 15 minutes before the 2 hours was up, moisture readings were taken and recorded. This was done so that the water could be turned on exactly at the 2-hour mark, without disrupting any of the reading locations. If any of the measurement locations became submerged, the moisture reading was recorded as 100% moisture. Instead of taking readings at every location, the readings that were recorded are the first location where the moisture read above 17.0%. According to the Moisture Meter, this percent moisture would be considered "At Risk."

At the end of the first day, the water level was 14 inches from the bottom of the pool. Contrary to the first flood test, the water was drained each evening to pause the test until the following morning when it was resumed. This was done because measurements were taken more frequently and therefore could not be completed without intermission. On the second day, the test was resumed, starting at 16 inches, which was the next scheduled flood depth to be tested. The process of filling up to 16 inches took nearly two hours and therefore the measurement timeline had to be pushed back. At the end of the day, before draining the pool for the night, the water level was at 28 inches. The next morning, water was filled to 30 inches. However, this time, it took approximately 4 hours to fill the pool to the necessary depth. It must be noted that although it took 4 hours to fill the pool, the water also needed to soak for 2 full hours before any measurements could be read and recorded. Salt was also added every time the pool was filled to maintain the 3500ppm saltwater content.

When it was time to take the readings at 34 inches, the Protimeter Surveymaster Moisture Meter long probes became unresponsive and therefore only half of the designated measurements could be taken. At this point, it was determined that there was sufficient data to complete an analysis and that it would be okay to end the flood test and drain the pool completely. The same Honda pump from the first flood test was utilized to drain the water each day of this second flood test. The next day, the structure was stripped. Materials that would not be used in future flooding events or deemed irreparable were discarded while those that could be reused were documented.

CHAPTER 4

DATA ANALYSIS METHODOLOGY AND RESULTS

4.1 Introduction

The data collected from the flood tests were documented in Microsoft Excel. From the freshwater flood test, over 3200 data points were collected using the Protimeter Surveymaster Moisture Meter to obtain the percent moisture content. The second flood test produced over 4500 data points. On each wall, lines were drawn every 3 inches from the floor. Holes were drilled through the paper-faced gypsum panel to allow the longer probes to reach the 2”x4” studs, the insulation, and the baseplate of the structural frame for moisture measurements. The structure walls were labeled as Wall 1, Wall 2, Wall 3 and Wall 4 as shown in **Figure 4-1** for ease of identification when taking measurements.

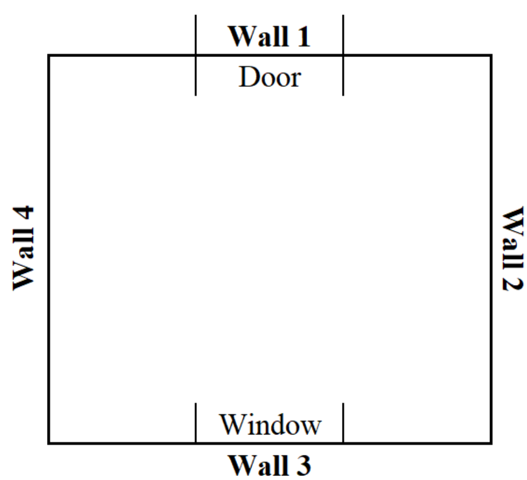

Figure 4-1: Wall Identification

To take measurements of the paper-faced gypsum panel, the needle-like probes directly on the Moisture Meter were used.

4.2 Measurements

4.2.1 Freshwater Flood Test

The elevation was considered 0" at the floor level of the structure. Therefore, the bottom of the pool and foundation was considered to be -6" below baseline elevation. For the first 5 readings, baseline (no water), water at -3', water at 0", water at 3", and water at 6", only 3 readings were taken up the wall. This was done because no absorption was expected at such low flood levels, so excess data points would have been futile for future analysis purposes. A diagram of Wall 2 with the measurement locations, where the two points are each located, for the first 8 hours (5 readings) is shown below in **Figure 4-2**.

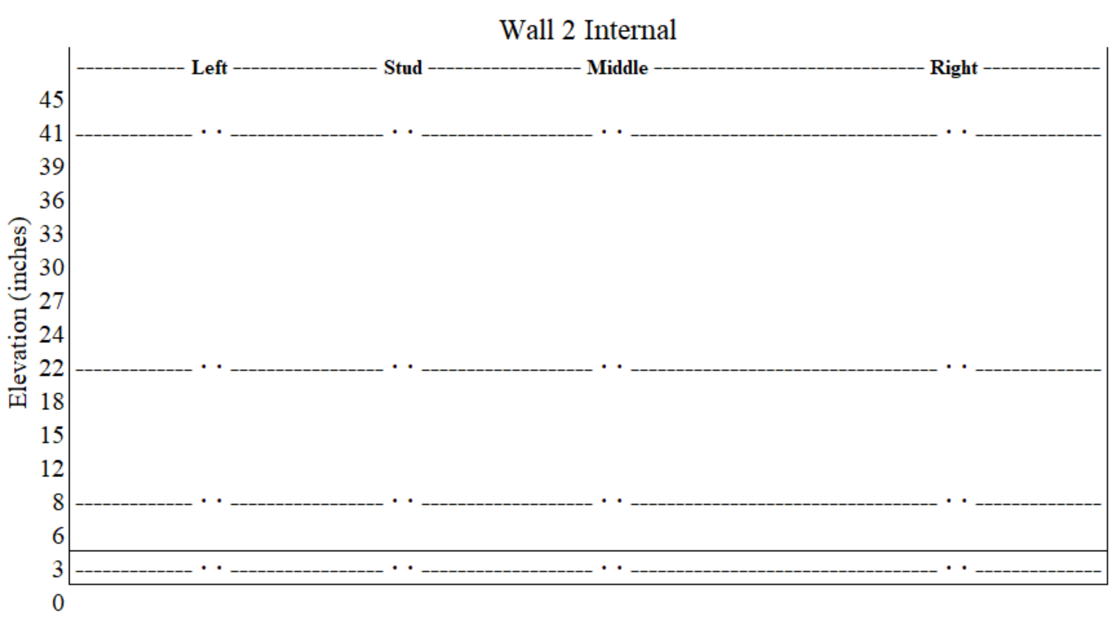

Figure 4-2: Wall 2 Internal Measurement Locations for Freshwater Test

The gypsum paneling and insulation were measured at each location where there are two dots: Left, Middle, and Right at 8", 22", and 41". The base plate was measured as well at the 3” elevation at the Left, Middle, and Right locations. A stud was measured up the column labeled “Stud” at 8”, 22”, and 41”. Floor measurements were taken using the non-invasive Search mode measurement until the water reached inside the structure and then the flooring was deemed 99.9% moisture content. After reading #5, it was decided that more frequent readings up the walls were necessary to fully understand the absorption properties of the construction materials. These additional readings were taken every 6 inches as shown in **Figure 4-3**.

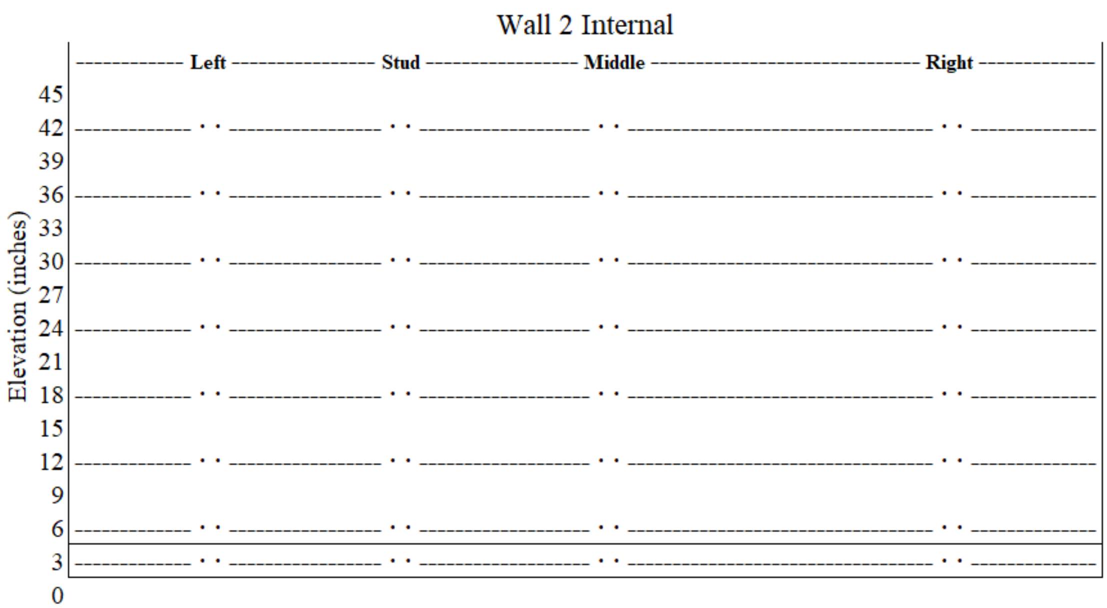

Figure 4-3: Wall 2 Internal Measurement Locations after Reading #5 for Freshwater Test

On the outside of the structure, holes were also drilled through the siding so that measurements of the underlying OSB sheathing could be taken. Taking measurements of the siding was done using the non-invasive Search mode measurement. By placing the back of the meter on various surfaces that could not be probed, such as the flooring, door, window frame, foundation, and siding, the moisture condition could be identified up to

¾” beneath the surface. The locations of the external measurements can be seen in **Figure 4-4**.

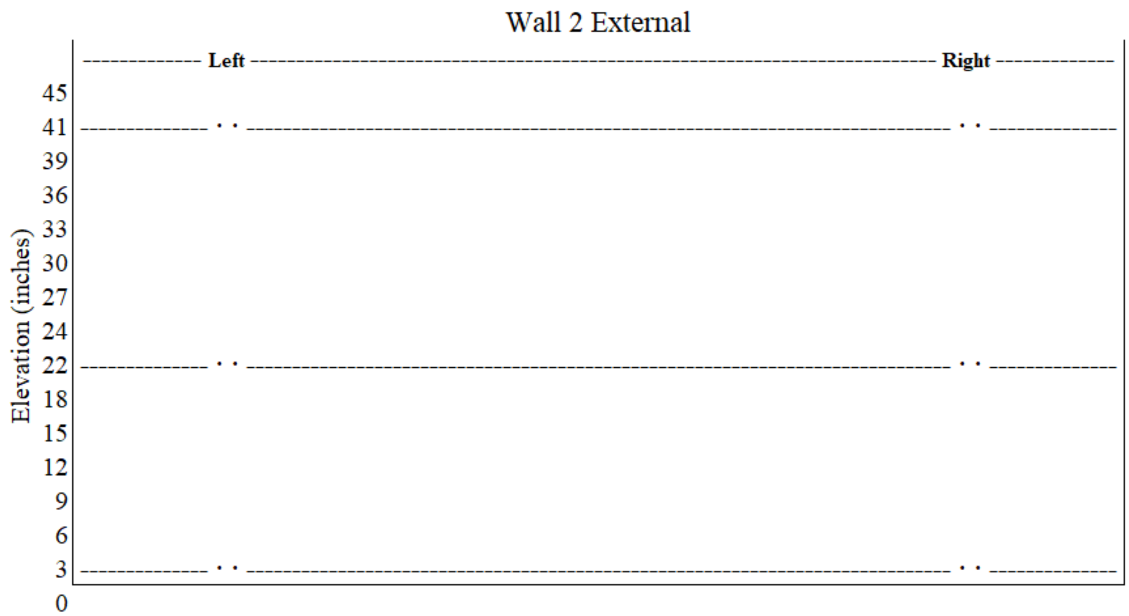

Figure 4-4: Wall 2 External Measurement Locations for Freshwater Test

Measurements were taken until the water level reached 36 inches within the swimming pool.

4.2.2 Saltwater Flood Test

During the second flood test, a different method for obtaining moisture measurements was utilized. This was due in part to the excessive amount of seemingly futile data points that were taken up the wall, much higher than the water could have even absorbed. Some measurement methods were kept the same, such as the surface readings of the flooring, door, window frame, foundation, and external siding using the non-invasive Search mode measurement.

However, inside the structure, the wall reading method was changed. As shown in Image #, on the Left side under the column of “S” which stood for “Stud,” ⅛ diameter holes had to be drilled to reach through to the stud. The long probes of the Protimeter Surveymaster were then used to read vertically across two holes. For instance, one probe was put in at 4 inches and then another one was put in at 5 inches. This allowed for the meter to determine if the vertical space between the probes would be considered Wet. Two measurements were recorded. The highest measurement on the wall reading Wet or At-Risk and the lowest measurement on the wall reading Dry. This would provide enough data to determine where within those two readings the materials transitioned from Wet to Dry. The same procedure was repeated but for the “I” column which stood for “Insulation.” The paper-faced gypsum paneling was also read at those height measurements but by using the short needle probes on the Protimeter and puncturing into the paper-faced gypsum paneling. The measurement locations were not exactly predetermined and equally spaced out as they were in the freshwater flood test. After the pool was drained, the heights of every measurement hole were recorded. A diagram of how the measurements were taken is shown in **Figure 4-5**. At the 1.5-inch measurement location, ⅛” diameter holes were drilled to be able to read into the baseplate of the structural framing. It was also determined that the outside of the structure needed more measurement locations as shown in **Figure 4-6**. Holes were drilled through the siding so that measurements of the underlying OSB sheathing could be taken with the long Protimeter probes. Taking measurements of the siding, itself, was done using the non-invasive Search mode measurement.

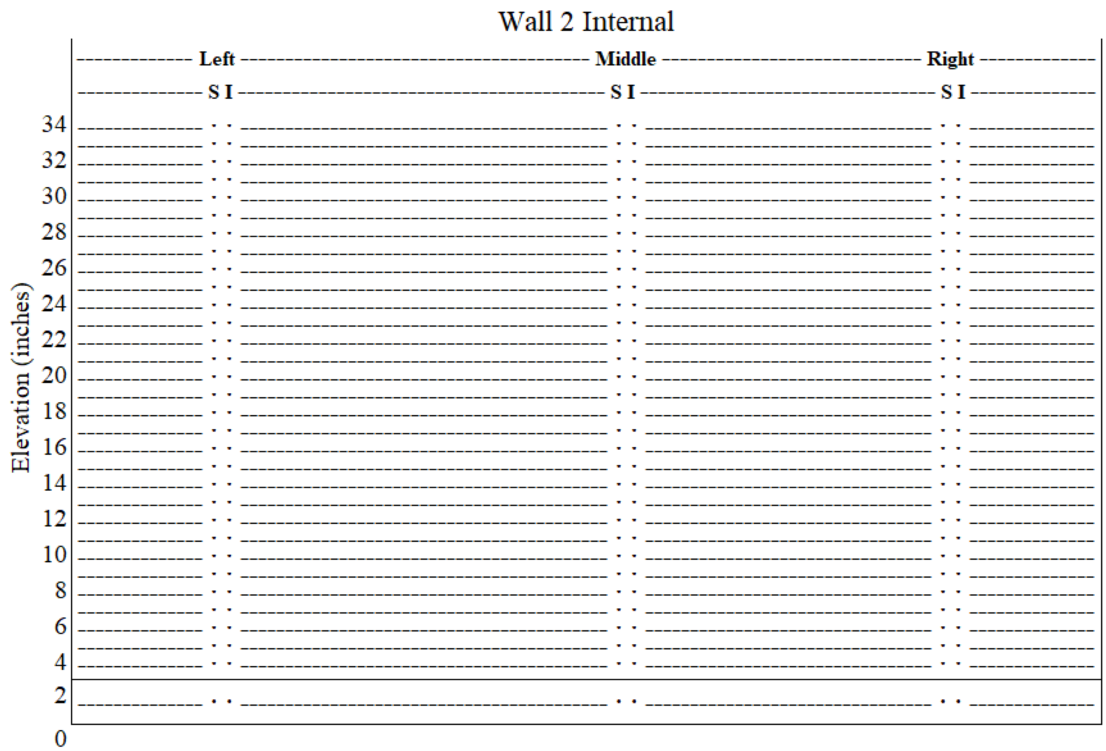

Figure 4-5: Wall 2 Internal Approximate Measurement Locations for Saltwater Test

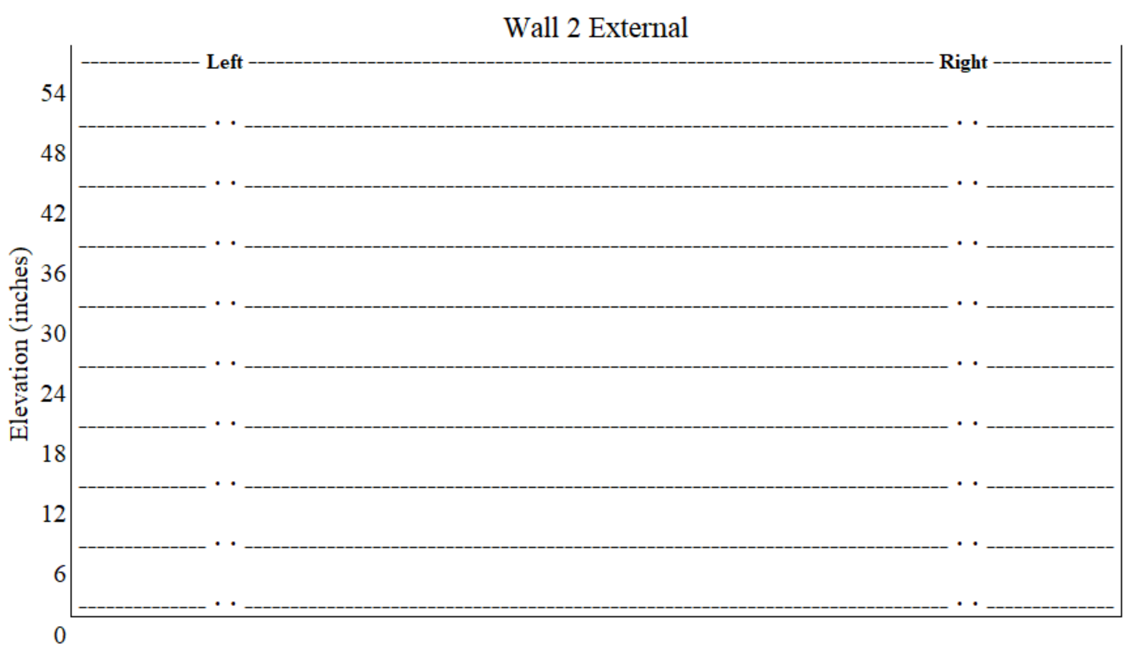

Figure 4-6: Wall 2 External Approximate Measurement Locations for Saltwater Test

4.3 Database Development

The purpose of developing the material database was to provide a resource for determining damage based on an individual material component level for a house. The initial step in organizing the raw data was to separate the moisture content measurements based on material, as shown in **Figure 4-7**.

Reading at 2:30pm Water at 2 in								
Paper Gypsum Paneling & Paint								
	Wall 1		Wall 2		Wall 3		Wall 4	
	MC	Height	MC	Height	MC	Height	MC	Height
L	11.7	3.5	12.4	5	10.2	5.5	12.2	5.5
M	None	None	10.7	5	11.8	6	11.4	6.25
R	15.4	3.75	11	5	12.7	5.75	10.8	5.25

Base Plate								
	Wall 1		Wall 2		Wall 3		Wall 4	
	MC	Height	MC	Height	MC	Height	MC	Height
L	99	1	99	1	99	1	99	1
M	99	1	99	1	99	1	99	1
R	99	1	99	1	99	1	99	1

Stud								
	Wall 1		Wall 2		Wall 3		Wall 4	
	MC	Height	MC	Height	MC	Height	MC	Height
L	10.8	3.25	9.2	4.5	10.8	5	10.1	5
M	None	None	11.4	4	10.8	5	8.6	5.75
R	57.3	3.25	11	4.5	10.2	5	10.2	4.75

Insulation								
	Wall 1		Wall 2		Wall 3		Wall 4	
	MC	Height	MC	Height	MC	Height	MC	Height
L	10.3	3.25	6.9	4.5	8.2	5	6.9	5
M	None	None	8.5	4	6.9	5	6.9	5.75
R	10.1	3.25	8.2	4.5	6.9	5	6.9	4.75

Figure 4-7: Section of the Raw Data Spreadsheet from the Saltwater Flood Test

As an example, when the paper gypsum paneling measurements were taken, there were three measurements along the length of the wall: at the Left, Middle, and Right locations as previously displayed in **Figure 4-5**. These moisture content values were then reviewed to determine if the material would be considered Dry, At Risk, or Wet. The ranges are shown in **Figure 4-8**.

The moisture measurements were immediately converted from percent moisture to percent damage based on the total amount of the specific material for the wall. The height correlates to the height of the measurement taken on the wall. The percent damage values were found by utilizing an IF statement to initially determine if the measured percent moisture was "At Risk" or "Wet." Materials were considered damaged if the percent moisture was above the Dry threshold of 17% moisture content as shown in **Figure 4-8**. The equation would then divide the area damaged by the total area and multiply it by 100 to get the percent damage of a specific material for each wall.

Moisture Meter Range	
No Reading	≤ 6.9
Dry	7.0 - 16.9
At Risk	17.0 - 19.9
Wet	≥ 20.0

Figure 4-8: Protimeter Surveymaster Moisture Content Reading Ranges

The paper-faced gypsum paneling can be seen in **Figure 4-9** as an example of the moisture measurements being directly converted to percent damage across each wall at the left, right, and middle locations. The red values show that there was any amount of damage, even if it was 1%. The green values show no damage, based on moisture values that were reading "Dry." For example, on the left side of Wall 1, with a 4in flood depth, at a measurement height of 5in, the moisture meter read At-Risk or Wet and therefore 4.73% damage was calculated.

2in								
	Wall 1		Wall 2		Wall 3		Wall 4	
	% Damage	Height	% Damage	Height	% Damage	Height	% Damage	Height
L	0.00	3.5	0.00	5	0.00	5.5	0.00	5.5
M	None	None	0.00	5	0.00	6	0.00	6.25
R	0.00	3.75	0.00	5	0.00	5.75	0.00	5.25

4in								
	Wall 1		Wall 2		Wall 3		Wall 4	
	% Damage	Height	% Damage	Height	% Damage	Height	% Damage	Height
L	4.73	5.00	5.23	5.00	8.53	5.50	5.76	5.50
M	None	None	5.23	5.00	9.30	6.00	6.54	6.25
R	5.20	5.50	5.23	5.00	8.91	5.75	7.07	6.75

6in								
	Wall 1		Wall 2		Wall 3		Wall 4	
	% Damage	Height	% Damage	Height	% Damage	Height	% Damage	Height
L	6.15	6.50	7.59	7.25	12.40	8.00	8.11	7.75
M	None	None	7.85	7.50	12.40	8.00	9.16	8.75
R	6.38	6.75	8.11	7.75	12.02	7.75	8.37	8.00

Figure 4-9: A Section of the Percent Damage Calculations for Paper-faced Gypsum Paneling from Saltwater Flood Test

From here, the minimum, average, and maximum of the left, middle and right data points were calculated. These were organized into separate tables to view each set of data as shown. The final values were brought into a larger table compiled of each material. **Figure 4-10** only shows the section of the final compilation for the paper-faced gypsum paneling. The entire set of data can be found in APPENDIX A.

	Paper Gypsum Paneling & Paint											
	Percent Damage											
	Wall 1			Wall 2			Wall 3			Wall 4		
Height of Floodwater	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
-6	0	0	0	0	0	0	0	0	0	0	0	0
-4	0	0	0	0	0	0	0	0	0	0	0	0
-2	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
4	4.7	5.0	5.2	5.2	5.2	5.2	8.5	8.9	9.3	5.8	6.5	7.1
6	6.1	6.3	6.4	7.6	7.9	8.1	12.0	12.3	12.4	8.1	8.5	9.2
8	8.7	9.1	9.5	9.9	10.0	10.2	15.5	15.9	16.3	10.5	11.3	11.8
10	13.7	14.4	15.1	14.1	14.7	15.2	19.4	22.6	25.1	16.7	17.2	18.1
12	15.4	16.2	17.0	15.2	16.0	17.0	24.5	25.4	26.3	18.1	18.8	19.9
14	16.3	16.7	17.0	16.5	16.7	17.0	24.5	25.4	26.3	16.7	18.2	19.9
16	16.3	16.7	17.0	18.1	18.6	19.1	25.9	26.1	26.3	19.4	19.8	20.1
18	18.4	18.4	18.4	19.9	20.2	20.4	26.9	27.5	28.1	21.2	21.3	21.5
20	19.6	20.0	20.3	21.5	22.4	23.0	28.9	29.1	29.3	22.5	23.1	23.6
22	21.7	21.7	21.7	23.8	24.2	24.3	29.7	30.1	30.5	24.6	25.5	26.2
24	25.5	25.8	26.0	25.9	27.5	28.3	32.8	32.8	32.8	27.2	27.6	28.0
26	26.7	27.1	27.4	28.3	28.8	29.3	33.6	33.7	33.8	28.8	29.9	31.4
28	27.7	28.0	28.4	29.8	30.6	31.4	34.8	34.9	35.0	30.4	31.2	32.7

Figure 4-10: Final Table for Percent Damage of Paper-faced Gypsum Paneling from Saltwater Flood Test

From this database, depth-damage curves can be created for individual materials. **Figure 4-11**, **Figure 4-12**, **Figure 4-13**, and **Figure 4-14** are the depth-damage curves of the paper-faced gypsum paneling for each of the four walls. The mean is linearly plotted with the minimum and maximum percent damage creating a range around the mean.

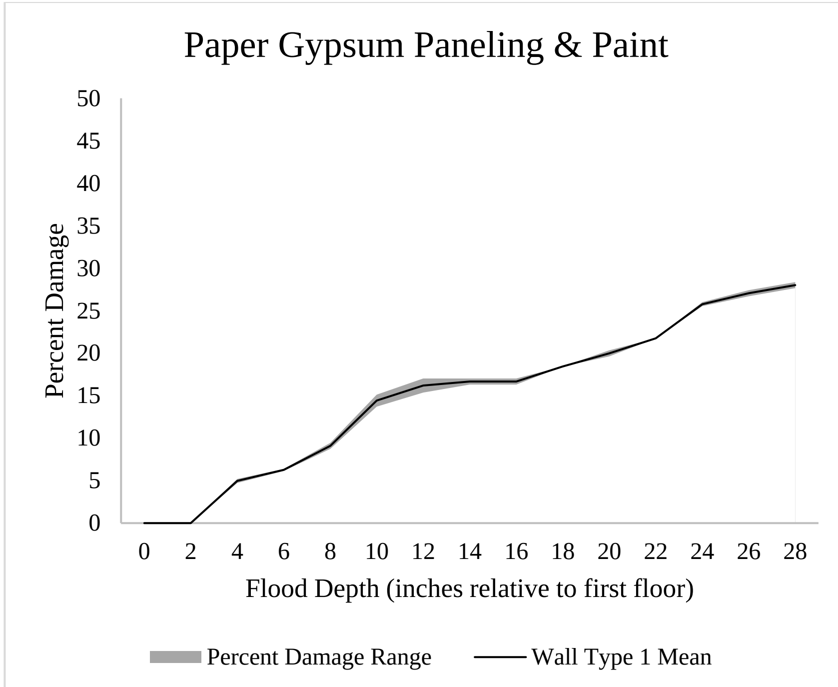

Figure 4-11: Wall 1 Depth-damage Curve from Saltwater Flood Test

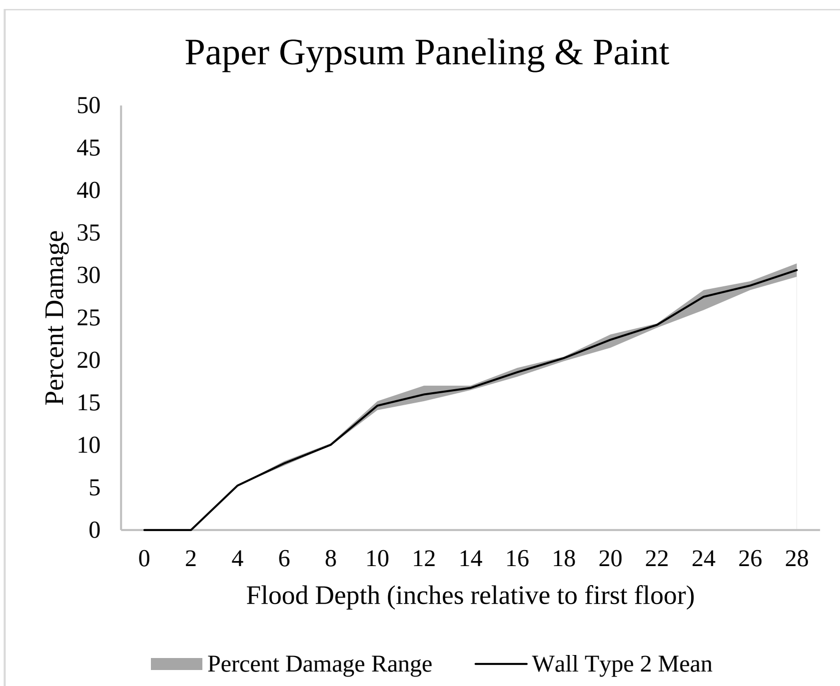

Figure 4-12: Wall 2 Depth-damage Curve from Saltwater Flood Test

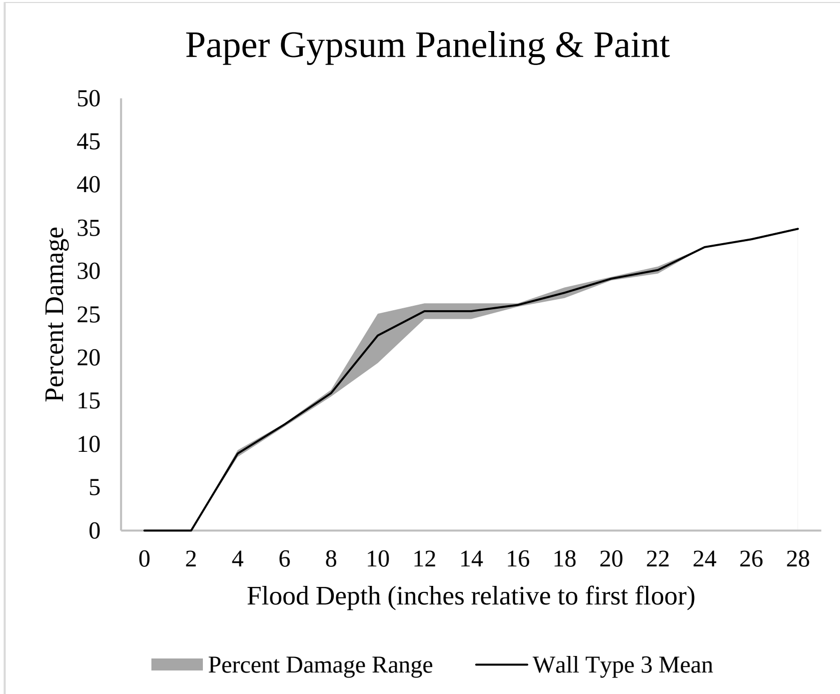

Figure 4-13: Wall 3 Depth-damage Curve from Saltwater Flood Test

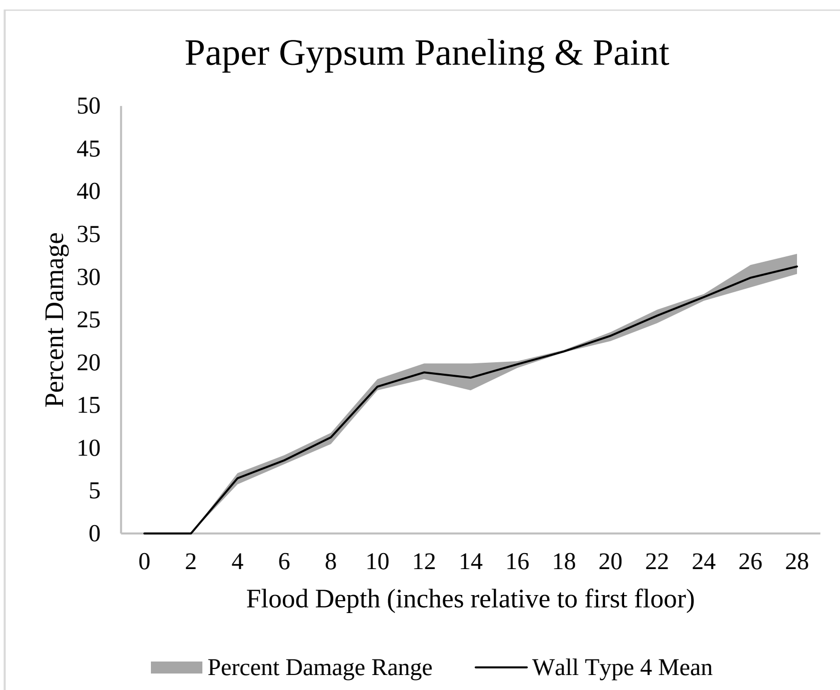

Figure 4-14: Wall 4 Depth-damage Curve from Saltwater Flood Test

These component depth-damage curves only relay raw physical damage to the materials themselves. They do not encompass any restoration or labor costs that could be associated with a flooding event, cleanup, or repairs afterward.

In **Figure 4-15**, the averages of all four walls are plotted to compare the different wall assemblies and their effectiveness to resist damage during flood events.

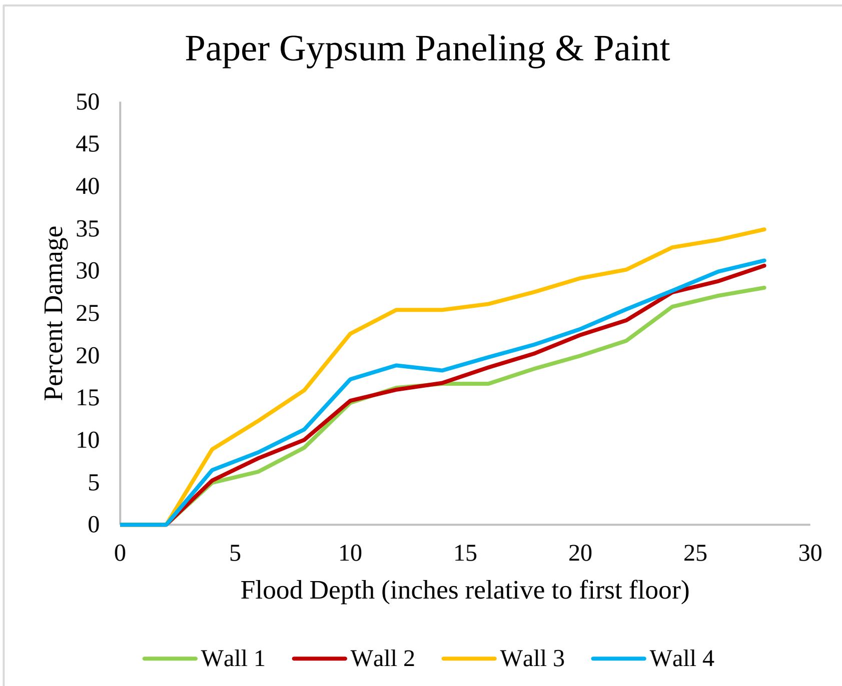

Figure 4-15: Comparison of Walls 1-4 Depth-damage Curves

All of the material data and depth-damage curves for both the freshwater and saltwater tests can be found in APPENDIX B.

4.4 Restoration Analysis of Materials

When the materials were being removed from the main structure frame, they were analyzed to determine the next best course of action for each one. While some materials had to be immediately disposed of, others were set aside with the intent of restoration.

The fiberglass batt and paper-faced gypsum paneling were discarded as there was no way to restore them to their original functioning state. The 1-gang plastic outlet box was removed from the stud. The plastic box itself could be reused but due to the salt content of the water, the nails utilized to hold the box in place were rusted and will need to be replaced. Upon first inspection, the electrical outlet did not appear to have any damage, however, some of the screws were also rusted. The wire showed some evidence of corrosion where it was stripped and connected to the outlet. The ground wire had no insulation and only showed evidence of water damage within the portion that was stripped of the entire casing and used within the plastic box. The wire that was encased in the insulation was split open to assess the condition and there was no visible damage to the internal wiring for the entire length up the wall. The electrical outlet and wiring were only installed for the saltwater flood test. The engineered hardwood flooring was removed and set aside to dry; however, mold became a large issue and they had to be thrown away. The vinyl tiles were removed and thrown away as the adhesive was no longer functioning as it was intended.

The ceramic tiles were destroyed when removed from the wood subfloor side to allow for the subfloor to dry out as much as possible. On the concrete subfloor side, the ceramic tiles did, however, stay intact and installed and were able to be reused for the second flood test. The foam boards were easily slid out from the walls and laid out to dry. All of the baseboards and trim were uninstalled and set aside for drying.

Table 4-1 shows all materials that were discarded, restored, or untouched following the first flood.

Table 4-1: Material Assessment List Following the First Flood Test

Material	Discarded, Restored, Untouched
Concrete Foundation	Untouched
Wood Substructure	Untouched
Wood Frame	Untouched
Vinyl Siding	Untouched
Fiber Cement Siding	Untouched
Door and Frame	Untouched
Window and Frame	Untouched
Door Trim	Restored
Window Trim	Restored
Fiberglass Batt	Discarded
Foam Board	Restored
Paper Gypsum Paneling	Discarded
Engineered Hardwood	Discarded
Ceramic Tile	Discarded & Untouched
Vinyl Tile	Discarded
Baseboards	Restored

Once the foundation and structural frame of the house had sufficiently dried out, reconstruction took place. After fully drying out, the foam insulation boards were installed. The fiberglass batt had to be replaced with new material and following that, the new paper gypsum panels were installed. The panels were then taped, filled with a drywall joint compound, and painted. The majority of the flooring was discarded, therefore new flooring had to be installed. The only section that remained from the first flood event was the ceramic tiles that were installed on the concrete subfloor. The salvaged baseboards, window trim, and door casing were sanded down and repainted. These pieces were easily reinstalled with little to no variation from their original installation. A majority of the rubber coating had peeled up during the draining process and therefore needed to be resealed. Two new coats of liquid rubber coating were applied in preparation for the second flood test.

After the second test, in preparation to completely rebuild the structure for later tests, many materials were removed even though they could have withstood further flood tests. **Table 4-2** lists out the materials that were determined to be discarded, restored, untouched or set aside after the saltwater flood test. These materials are marked as "Set Aside" because they have more useful life still left but they will not be needed for further tests. The restored items will be utilized for later flood testing.

Table 4-2: Material Assessment List Following the Second Flood Test

Material	Discarded, Restored, Untouched, Set Aside
Concrete Foundation	Untouched
Wood Substructure	Discarded
Wood Frame	Restored
Vinyl Siding	Set Aside
Fiber Cement Siding	Set Aside
Door and Frame	Restored
Window and Frame	Restored
Door Trim	Restored
Window Trim	Restored
Fiberglass Batt	Discarded
Foam Board	Set Aside
Paper Gypsum Paneling	Discarded
Engineered Hardwood	Discarded
Ceramic Tile	Discarded
Vinyl Tile	Discarded
Baseboards	Discarded

4.5 Conclusion

After the freshwater flood test, an alternate method for obtaining data points was utilized for the saltwater flood test to obtain more data points. The database was then created by converting percent moisture content readings into percent damage based on material quantities in the structure. The percent damages were then compiled and combined to produce depth-damage curves based on material for each wall assembly. A combination of all four wall assemblies was plotted to compare the curves against each other. When materials were removed from the structure, they were visually inspected to determine if they could be untouched, restored or discarded. The following chapter thoroughly discusses the data and materials.

CHAPTER 5

INTERPRETATION OF RESULTS

5.1 Introduction

In this chapter, the data collected from the freshwater and saltwater flood tests are contrasted to observe the differences in damage based upon water type. The depth-damage curves are also reviewed and compared against other existing depth-damage curves to determine if variation exists between the curves created in this study and existing curves used in practice.

5.2 Results

Since the data were collected in two different methods throughout each flood event, this led to some differences in the portrayal of the data. Overall, the trend of every depth-damage curve displayed a positive correlation of flood depth to percent damage; as flood depth increased, the percent damage increased. This was the expected outcome; however, the saltwater test more accurately portrays a larger set of data. By taking the highest moisture content at the tallest location at each of the three measurement columns, the data can reflect the moisture absorption of the materials. The freshwater data was more controlled at the specific measurement locations which led to the more linear stepped plots.

It can be noticed on the material depth-damage curves for the freshwater flood test, that there is a dip in nearly all the curves at the 9in flood depth. This is attributed to the switch in measurement locations when the flood depth was at 9 inches. Before 9 inches, there were only three measurement locations, 8 inches, 22 inches, and 41 inches. When the flood depth reached 9 inches, it was deemed necessary to take more frequent measurements to fully encapsulate the reactivity of the materials within the wall assemblies. Therefore, the measurements read at 8 inches, which read the absorption underneath, at 9 inches, where nothing had happened quite yet, and then continued upwards in increments of 6 inches. Since the saltwater test did not reach as high of a flood level as the freshwater test did, due to equipment failure, the comparison of the data sets was made between 0 and 28 inches, where 0 represents the first-floor elevation.

5.3 Material Comparison of Freshwater and Saltwater Tests

5.3.1 Paper-faced Gypsum Paneling

The paper-faced gypsum paneling (sheetrock) expressed variance for the material measurements based on material combinations. The measurements also read at least 17% moisture well above the actual flood depth. This is likely due to the absorptive nature of the paper facing and gypsum. The freshwater test produced data that revealed the paper-faced gypsum paneling absorbed more water and therefore assumed more damage than was experienced in the saltwater test. It can be noted that Wall 3 and Wall 4 had higher percent damage and these two wall combinations included the foam board as opposed to Walls 1 and 2 containing the fiberglass batt insulation.

5.3.2 Baseplate

The baseplate of the wall frame was tested more so for documentation purposes than to see the damage inflicted. It was determined that the baseplate did not absorb any water that was below the first-floor elevation of the foundation. The baseplate was not removed as it was part of the structural framing.

5.3.3 Studs

The studs showed no variance during the freshwater test but did show a narrow range of values from the saltwater flood test. The studs did show absorption by exhibiting Wet or At-Risk moisture readings above the actual flood depth. Similar to the baseplate, the studs were not removed because they are part of the structural framing. The studs showed no direct effect from the varying wall material combinations. The values are close and display no noticeable variance.

5.3.4 Insulation

The insulation also showed no range in the freshwater test but did from the saltwater test. The insulation also showed higher damage values for the saltwater test which indicates that there was more absorption of the saltwater than the freshwater. It was expected that the fiberglass batt would show more absorption than the foam board but there seem to be no noticeable differences between the two. However, unexpectedly, Wall 3, the wall with the window and full wood-frame foundation, had the highest absorption through the insulation in the saltwater test. From the freshwater test, the two walls without any openings, Walls 2 and 4, had the highest absorption.

5.3.5 Siding

The siding of the structure was also measured for percent moisture; however, this data was also just for documentation purposes. The siding of a structure is intended to protect the structure from the outdoor elements and therefore, any absorption or damage was not expected. Throughout both the freshwater and saltwater tests, the fiber-cement siding experienced more absorption than the vinyl siding. The siding performed as expected. Both siding types protected the outside of the structure while still being able to be reused with useful life remaining after the two flood tests.

5.3.6 OSB Sheathing

The oriented strand board (OSB) sheathing is another structural component and was not intended to be removed during the restoration phase. The OSB sheathing endured more damage from the saltwater test than from the freshwater test. Some absorption was detected during the saltwater test. The freshwater test had much fewer data points up the external wall, only 3, and therefore it is difficult to determine if there was any absorption. Walls 3 and 4 displayed the most damage. Wall 3 was affixed on the full wood-frame foundation so there may have been some absorption through the foundation that contributed to the higher values. There also may have been some shared absorption with the fiber-cement siding that could have contributed to higher percent damage values.

5.4 Comparison to Existing Depth-Damage Curves

Existing depth-damage curves include those prepared by the U.S. Army Corps of Engineers (USACE) and Gulf Engineers & Consultants (GEC). These are the commonly referenced depth-damage curves, with the GEC curves specifically developed for use in Louisiana. The USACE depth-damage curves are based on historical data, while the GEC curves are based on synthetic expert opinion. The first comparison drawn is between the experimental depth-damage curves created from the developed flood material damage database and the synthetic material curves from GEC.

Figure 5-1 and **Figure 5-2** show a comparison of the GEC 2006 synthetic material curve to the experimentally collected material data of the four wall assemblies from this study. Both the salt and freshwater experimental data are shown. The GEC data extends to a 15-foot flood depth but because this flood study only reached a flood depth between 2 and 3 feet, the GEC data was cropped to fit the experimental data. The GEC curves greatly overestimate the damage to the structures. It is important to note that the experimental percent damage was not calculated from costs and therefore does not include any repair or restoration costs associated with each material.

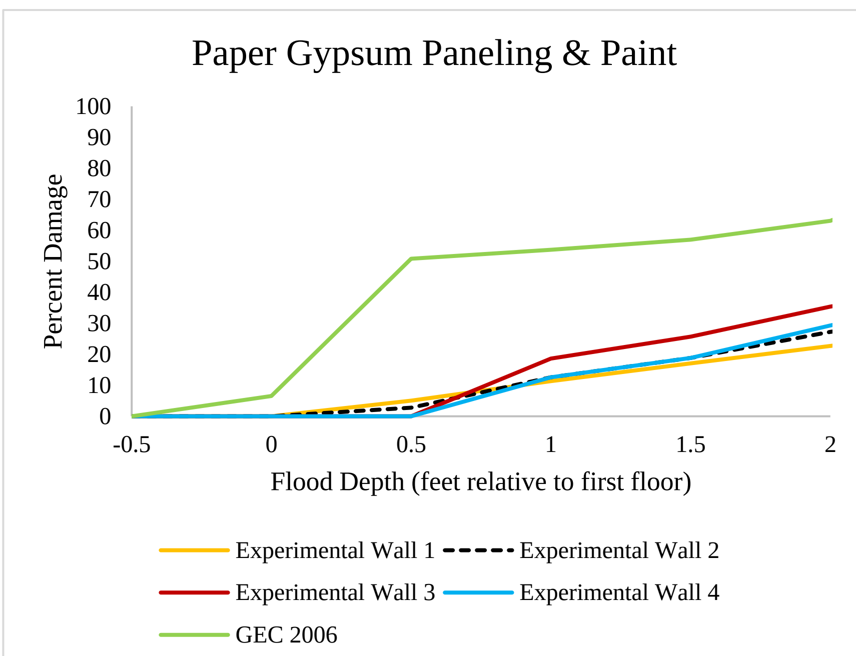

Figure 5-1: Freshwater Depth-damage Curve Comparison

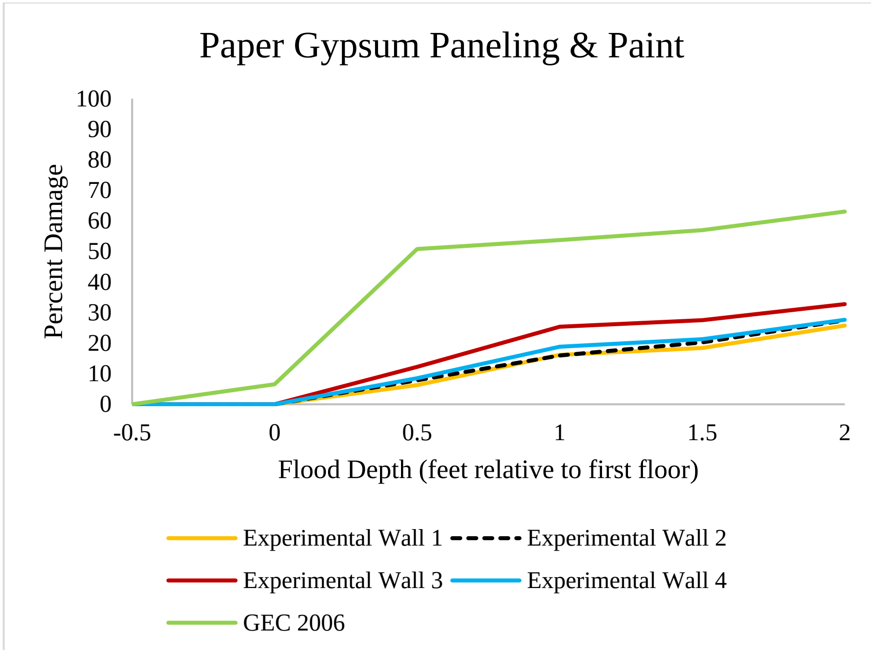

Figure 5-2: Saltwater Depth-damage Curve Comparison

To further compare the experimentally collected data with existing depth-damage curves, the data was plotted against the GEC residential building curves for slab and pier foundations and the USACE single-family residential building curve for one-story structures without basements. The experimental building curves were made based on information from the GEC damage tables. The materials that the experimental flood tests collected damage data for were replaced into the GEC damage values. Because some materials and consumer goods were not tested in the experimental flood tests, those values were pulled from the GEC itemized damage tables. This allowed the experimental material data to be compared with the building depth-damage curves produced by GEC and USACE.

The GEC curves for freshwater and saltwater are identical so only the freshwater curves are shown in **Figure 5-3**. As it can be seen, the GEC pier foundation has the highest estimation for damage. The experimental curves closely follow the GEC slab foundation curve.

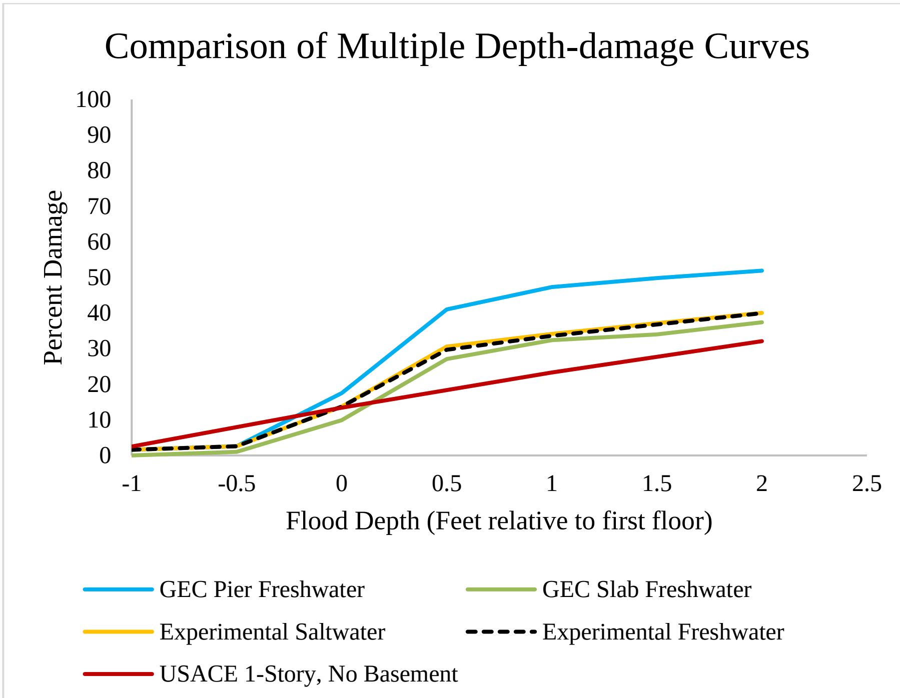

Figure 5-3: Depth-damage Curve Comparison

The experimental curves were developed by averaging all four wall assemblies. There was no drastic difference between taking the average, maximum, or minimum of the wall assembly percent damage values, so taking the average was deemed appropriate. The linear trend of the USACE curve displays that the damage is overestimated under a flood depth of zero, relative to the first-floor elevation, and underestimated for flood depths greater than zero. Because of this linear trend, the USACE depth-damage curve does not vary much as depth increases even though it is evident on the other curves that after a certain depth, the damage does change at a varying rate. The data spreads as the flood depth increases showing that there is a noticeable variability among the different methods for creating depth-damage curves. This comparison supports the idea that further investigations of material damages are necessary to hone in on the actual damage inflicted by floods.

5.5 Conclusion

The different materials did present varying absorption depending on the flood test, freshwater, or saltwater. This is important to note because GEC assumes the depth-damage curves are identical for both fresh and saltwater. The comparison of the GEC, USACE and Experimental curves proves the variance among the different methods and further supports the demand for a uniform flood loss analysis model. The next chapter presents some concluding thoughts and observations on the present work as well as direction for future work to fully develop a model.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusion of Present Work

A review of relevant literature on flood loss prediction models presented the scarcity of experimentally collected flood damage data. This opportunity to construct and test built structures for the damage inflicted by flooding provided insight into material reactivity when subjected to various short-term flood depths. The wall construction that consistently had the most percent damage inflicted upon it was Wall 3. This wall was on the full wood-frame foundation, had foam insulation, fiber-cement exterior siding, and a window. It is likely that having the opening in the wall encouraged more water to enter, as opposed to only having damage inflicted based on absorption throughout a continuous wall.

The collected moisture content data reveals that many construction materials do experience damage above the flood water depth, which should be taken into account when processing depth damage curves. The existing curves either over or underestimate the damage inflicted on the materials. From the comparisons made in Chapter 5, it appears that the GEC and Experimental curves follow a similar trend. The GEC Pier curve overestimates the damage compared to the GEC Slab curve that follows the Experimental curves well. The USACE linear trend underestimates the damage inflicted by a flood of depth greater than the first-floor elevation.

Based on the comparison of the experimental depth damage curves to the historic and synthetic depth damage curves, it can be concluded that further experimental data should be collected. This data further supports the development of a model that will potentially predict flood loss more accurately.

6.2 Future Work

While the present work provides some insight on the material component damage, further experimental testing can provide a broader range of knowledge into the validity of the synthetic and historical depth damage curves.

6.2.1 Expansion of Material Database through Future Testing

The structure that was tested only encompassed a single set of materials. Future plans for testing involve even more materials and combinations. Some of the materials included in the plan for future testing are brick, stucco, paperless gypsum, carpet, and hardwood flooring. Two more structures will be built, and each will be flood tested twice, with fresh and saltwater. Further testing of electrical components will also be included in future structures. This collection of material damage information will be processed and stored in the material database. This database will be one of the first to efficiently predict damage following a flood event based on collected experimental data.

6.2.2 Development of Accessible Model

With a solid and expansive material database, a model can be created to produce monetary assessments of loss following a flood event. The model will aim to assess the damage uncertainty on multiple scales including individual materials, specific wall types, and entire buildings. These can then be incorporated to estimate the loss in neighborhoods of similar buildings and then larger building groups. It will be interesting to find if, at a large scale, the inaccuracies cancel out. However, having an accurate foundation is integral in providing secure estimations for damage.

Figure 6-1 outlines the suggested framework for developing a model that can analyze flood loss at multiple scales. The ellipses represent the inputted data that would be necessary to produce the flood loss prediction. To start, anyone could utilize the model and input their building materials or building types under user inputs. They can then select whether the data would be processed as an individual building, a small group of buildings with similar construction, or a large group of buildings with differing constructions. A component-level damage database will be developed from the experimental testing and from there, individual curves can be combined to create total damage curves. These total damage curves will support the flood loss analysis portion of the model. The building value, flood data such as the height of floodwater, type of water e.g., saltwater or freshwater, and other flood parameters will also need to be input so that all the factors necessary for calculating a flood loss prediction cost will be included.

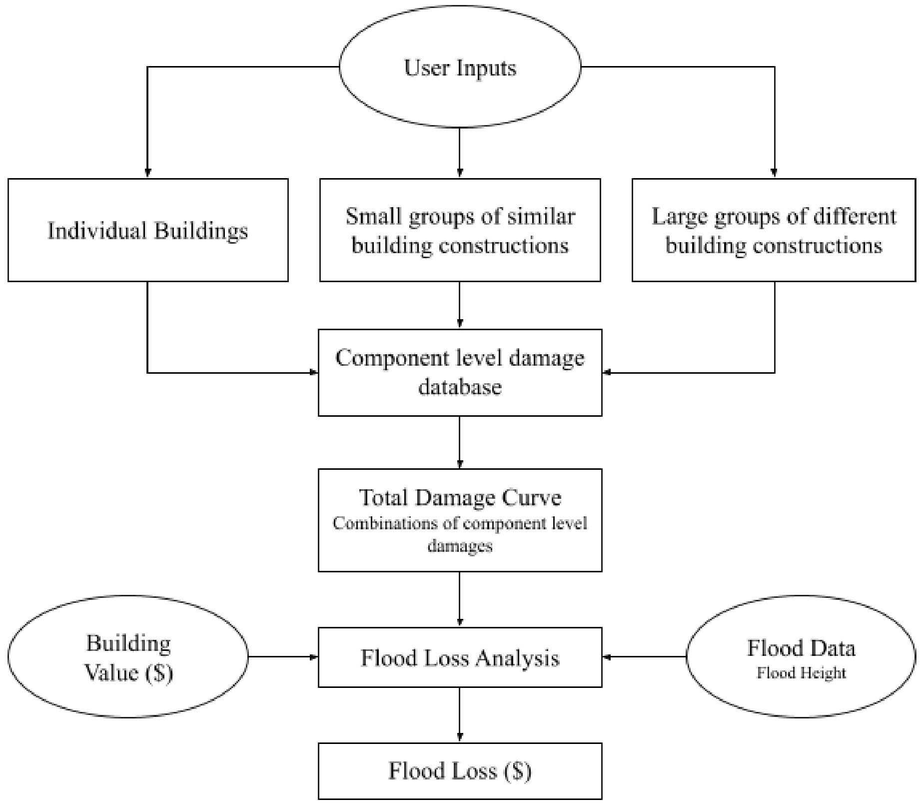

Figure 6-1: Framework for Modeling Process

This model will also incorporate other loss costs such as labor and restoration costs. The overall goal would be for the model to be accessible for anyone to use, whether it be inspectors, city planners, researchers, government officials or homeowners.

6.2.3 Applications

It is recommended that the flood loss prediction model be tested with known case studies. This will provide further analysis into the relevance of experimentally collected data and how it relates to the existing methods. This study has not only provided the foundation of a fundamental understanding of material damage but also prepares for the development of a more effective modeling tool for building community resilience through flood risk analysis and hazard mitigation planning.

APPENDIX A

EXPERIMENTAL DATA

A.1 Material Percent Damage Tables – Freshwater

Table A-1: Percent Damage Paper Gypsum Paneling and Paint – Freshwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00
12	11.35	12.56	18.60	12.56
15	11.35	12.56	18.60	12.56
18	17.02	18.84	25.69	18.84
21	17.02	18.84	30.55	25.12
24	22.69	25.12	35.41	25.12
27	28.37	31.40	35.41	31.40
30	28.37	31.40	45.14	43.96
33	34.04	37.68	50.00	37.68
36	34.04	37.68	50.00	43.96
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	5.04	2.79	0.00	0.00
9	0.00	0.00	0.00	0.00
12	11.35	12.56	18.60	12.56
15	15.13	14.65	22.15	16.75
18	17.08	18.84	25.69	18.84
21	20.80	23.03	30.55	25.12
24	22.69	27.21	35.41	29.31

Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
27	32.15	31.40	37.84	33.49
30	32.15	35.59	45.14	43.96
33	35.93	39.77	50.00	41.87
36	34.04	39.77	50.00	48.15

Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	7.56	8.37	0.00	0.00
9	0.00	0.00	0.00	0.00
12	11.35	12.56	18.60	12.56
15	17.02	18.84	25.69	18.84
18	17.20	18.84	25.69	18.84
21	22.69	25.12	30.55	25.12
24	22.69	31.40	35.41	31.40
27	34.04	31.40	40.27	37.68
30	34.04	37.68	45.14	43.96
33	39.71	43.96	50.00	43.96
36	34.04	43.96	50.00	56.52

Table A-2: Percent Damage Studs – Freshwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	7.88	0.00	0.00	0.00
6	7.88	0.00	7.03	7.49
9	0.00	0.00	0.00	11.23
12	11.82	11.23	11.23	11.23
15	17.73	11.23	11.23	16.84
18	17.73	16.84	16.84	16.84
21	23.65	22.46	16.84	16.84
24	23.65	22.46	22.46	22.46
27	23.65	22.46	22.46	22.46
30	29.56	28.07	28.07	28.07
33	35.47	33.68	33.68	33.68
36	35.47	39.30	33.68	39.30

Average Percent Damage				
Flood Height (in)	Wall 1	Wall 2	Wall 3	Wall 4
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	7.88	0.00	0.00	0.00
6	7.88	0.00	7.03	7.49
9	0.00	0.00	0.00	11.23
12	11.82	11.23	11.23	11.23
15	17.73	11.23	11.23	16.84
18	17.73	16.84	16.84	16.84
21	23.65	22.46	16.84	16.84
24	23.65	22.46	22.46	22.46
27	23.65	22.46	22.46	22.46
30	29.56	28.07	28.07	28.07
33	35.47	33.68	33.68	33.68
36	35.47	39.30	33.68	39.30
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	7.88	0.00	0.00	0.00
6	7.88	0.00	7.03	7.49
9	0.00	0.00	0.00	11.23
12	11.82	11.23	11.23	11.23
15	17.73	11.23	11.23	16.84
18	17.73	16.84	16.84	16.84
21	23.65	22.46	16.84	16.84
24	23.65	22.46	22.46	22.46
27	23.65	22.46	22.46	22.46
30	29.56	28.07	28.07	28.07
33	35.47	33.68	33.68	33.68
36	35.47	39.30	33.68	39.30

Table A-3: Percent Damage Insulation – Freshwater

Minimum Percent Damage				
Flood Height (in)	Wall 1	Wall 2	Wall 3	Wall 4
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	0.00	8.37	0.00	0.00
9	0.00	0.00	0.00	0.00

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
12	11.35	12.56	18.60	12.56
15	11.35	12.56	18.60	12.56
18	17.02	18.84	25.69	18.84
21	17.02	18.84	25.69	18.84
24	22.69	25.12	30.55	25.12
27	22.69	25.12	30.55	25.12
30	28.37	31.40	35.41	31.40
33	28.37	31.40	35.41	31.40
36	34.04	37.68	40.27	37.68
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	2.52	8.37	0.00	0.00
9	0.00	0.00	0.00	0.00
12	11.35	12.56	18.60	12.56
15	11.35	12.56	18.60	12.56
18	17.02	18.84	25.69	18.84
21	17.02	18.84	25.69	18.84
24	22.69	25.12	30.55	25.12
27	22.69	25.12	30.55	25.12
30	28.37	31.40	35.41	31.40
33	28.37	31.40	35.41	31.40
36	34.04	37.68	40.27	37.68
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	7.56	8.37	0.00	0.00
9	0.00	0.00	0.00	0.00
12	11.35	12.56	18.60	12.56
15	11.35	12.56	18.60	12.56
18	17.02	18.84	25.69	18.84
21	17.02	18.84	25.69	18.84
24	22.69	25.12	31.00	25.12
27	22.69	25.12	30.55	25.12
30	28.37	31.40	35.41	31.40
33	28.37	31.40	35.41	31.40
36	34.04	37.68	40.27	37.68

Table A-4: Percent Damage Siding – Freshwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	2.88	3.13	5.31	5.27
9	2.88	3.13	5.31	5.27
12	2.88	3.13	5.31	5.27
15	2.88	3.13	5.31	5.27
18	2.88	3.13	5.31	5.27
21	2.88	3.13	5.31	5.27
24	21.14	22.92	34.58	38.66
27	21.14	22.92	34.58	38.66
30	21.14	22.92	34.58	38.66
33	21.14	22.92	34.58	38.66
36	21.14	22.92	34.58	38.66
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	2.88	3.13	5.31	5.27
9	2.88	3.13	5.31	5.27
12	2.88	3.13	5.31	5.27
15	2.88	3.13	5.31	5.27
18	2.88	3.13	5.31	5.27
21	2.88	3.13	5.31	5.27
24	21.14	22.92	34.58	38.66
27	21.14	22.92	34.58	38.66
30	21.14	22.92	34.58	38.66
33	21.14	22.92	34.58	38.66
36	21.14	22.92	34.58	38.66
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
6	2.88	3.13	5.31	5.27
9	2.88	3.13	5.31	5.27
12	2.88	3.13	5.31	5.27
15	2.88	3.13	5.31	5.27

Maximum Percent Damage				
Flood Height (in)	Wall 1	Wall 2	Wall 3	Wall 4
18	2.88	3.13	5.31	5.27
21	2.88	3.13	5.31	5.27
24	21.14	22.92	34.58	38.66
27	21.14	22.92	34.58	38.66
30	21.14	22.92	34.58	38.66
33	21.14	22.92	34.58	38.66
36	21.14	22.92	34.58	38.66

Table A-5: Percent Damage OSB Sheathing – Freshwater

Minimum Percent Damage				
Flood Height (in)	Wall 1	Wall 2	Wall 3	Wall 4
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	3.13	5.31	5.27
6	2.88	3.13	5.31	5.27
9	2.88	3.13	5.31	5.27
12	2.88	3.13	5.31	5.27
15	2.88	3.13	5.31	5.27
18	2.88	3.13	5.31	5.27
21	2.88	3.13	5.31	5.27
24	21.14	22.92	34.58	38.66
27	21.14	22.92	34.58	38.66
30	21.14	22.92	34.58	38.66
33	21.14	22.92	34.58	38.66
36	21.14	22.92	34.58	38.66
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	3.13	5.31	5.27
6	2.88	3.13	5.31	5.27
9	2.88	3.13	5.31	5.27
12	2.88	3.13	5.31	5.27
15	2.88	3.13	5.31	5.27
18	2.88	3.13	5.31	5.27
21	2.88	3.13	5.31	5.27
24	21.14	22.92	34.58	38.66
27	21.14	22.92	34.58	38.66
30	21.14	22.92	34.58	38.66
33	21.14	22.92	34.58	38.66
36	21.14	22.92	34.58	38.66

Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-3	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
3	0.00	3.13	5.31	5.27
6	2.88	3.13	5.31	5.27
9	2.88	3.13	5.31	5.27
12	2.88	3.13	5.31	5.27
15	2.88	3.13	5.31	5.27
18	2.88	3.13	5.31	5.27
21	2.88	3.13	5.31	5.27
24	21.14	22.92	34.58	38.66
27	21.14	22.92	34.58	38.66
30	21.14	22.92	34.58	38.66
33	21.14	22.92	34.58	38.66
36	21.14	22.92	34.58	38.66

A.2 Material Percent Damage Tables – Saltwater

Table A-6: Percent Damage Paper Gypsum Paneling – Saltwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	4.73	5.23	8.53	5.76
6	6.15	7.59	12.02	8.11
8	8.75	9.94	15.50	10.47
10	13.71	14.13	19.38	16.75
12	15.36	15.18	24.47	18.06
14	16.31	16.49	24.47	16.75
16	16.31	18.06	25.89	19.36
18	18.44	19.89	26.90	21.20
20	19.62	21.46	28.93	22.50
22	21.75	23.81	29.74	24.60
24	25.53	25.91	32.78	27.21
26	26.71	28.26	33.59	28.78
28	27.66	29.83	34.80	30.35
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	4.96	5.23	8.91	6.45
6	6.26	7.85	12.27	8.55
8	9.10	10.03	15.89	11.25
10	14.42	14.65	22.57	17.18
12	16.19	15.96	25.38	18.84
14	16.66	16.75	25.38	18.23
16	16.66	18.58	26.09	19.80
18	18.44	20.24	27.51	21.28
20	19.97	22.42	29.13	23.11
22	21.75	24.16	30.14	25.47
24	25.76	27.48	32.78	27.65
26	27.07	28.78	33.69	29.92
28	28.01	30.62	34.91	31.23

Maximum Percent Damage				
Flood Height (in)	Wall 1	Wall 2	Wall 3	Wall 4
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	5.20	5.23	9.30	7.07
6	6.38	8.11	12.40	9.16
8	9.46	10.21	16.28	11.78
10	15.13	15.18	25.08	18.06
12	17.02	17.01	26.29	19.89
14	17.02	17.01	26.29	19.89
16	17.02	19.10	26.29	20.15
18	18.44	20.41	28.12	21.46
20	20.33	23.03	29.33	23.55
22	21.75	24.34	30.55	26.17
24	26.00	28.26	32.78	28.00
26	27.42	29.31	33.79	31.40
28	28.37	31.40	35.01	32.71

Table A-7: Percent Damage Studs – Saltwater

Minimum Percent Damage				
Flood Height (in)	Wall 1	Wall 2	Wall 3	Wall 4
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	4.43	3.74	4.68	4.68
6	4.19	5.15	7.02	6.78
8	8.62	7.72	7.95	9.59
10	11.08	10.76	11.46	11.23
12	12.81	11.93	12.40	13.10
14	13.79	13.10	13.57	14.50
16	15.02	14.04	14.97	15.67
18	16.50	17.08	16.84	18.71
20	20.20	18.95	19.88	20.12
22	22.17	20.12	21.05	21.52
24	23.15	23.63	23.16	22.46
26	26.35	24.09	25.50	23.86
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00

Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	1.60	0.00	0.00	0.00
4	5.30	4.37	5.93	5.30
6	5.67	6.08	7.02	7.41
8	9.11	8.27	8.27	10.21
10	11.33	11.07	12.01	11.85
12	13.30	12.48	13.22	13.96
14	13.92	14.04	13.80	14.89
16	15.76	14.97	15.79	16.14
18	17.12	17.62	17.19	19.10
20	20.20	19.73	20.82	20.66
22	22.17	20.90	22.11	22.30
24	24.01	24.09	23.74	23.70
26	26.72	24.41	26.90	24.95
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	3.20	0.00	0.00	0.00
4	6.16	5.15	7.02	5.85
6	7.14	6.55	7.02	7.72
8	9.61	8.65	8.89	10.99
10	11.58	11.70	12.87	12.40
12	13.79	13.57	14.04	15.67
14	14.04	14.50	14.04	15.67
16	16.50	15.44	16.61	17.08
18	17.73	18.01	17.54	19.65
20	20.20	20.12	21.75	21.05
22	22.17	21.52	23.16	22.92
24	24.88	24.56	24.33	24.33
26	27.09	24.56	28.30	25.73

Table A-8: Percent Damage Insulation – Saltwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
4	4.02	4.71	7.75	5.23
6	5.44	5.76	9.69	6.54
8	7.09	7.33	11.63	9.68
10	10.64	10.47	18.22	12.30
12	11.11	12.04	18.22	11.25
14	13.24	14.65	22.48	14.65
16	14.42	15.70	23.66	17.53
18	15.84	18.84	25.28	19.10
20	17.73	20.93	26.90	19.63
22	21.27	22.50	28.32	22.24
24	23.64	24.34	29.94	23.55
26	24.58	26.95	32.17	26.69
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	4.14	6.02	7.75	5.50
6	6.26	7.07	10.47	7.50
8	7.68	8.02	12.66	10.03
10	10.87	12.21	18.86	12.73
12	12.17	13.17	18.80	11.86
14	13.36	14.92	22.87	15.70
16	14.54	16.92	23.86	17.53
18	16.43	19.71	25.48	19.71
20	18.56	21.89	27.11	20.93
22	21.27	23.38	28.52	23.20
24	23.76	25.12	30.04	24.42
26	24.94	27.30	32.17	27.04
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	4.25	7.33	7.75	6.02
6	7.09	8.64	11.63	8.64
8	8.27	9.42	13.18	10.47
10	11.11	14.13	19.38	13.35
12	13.24	14.13	19.38	12.30
14	13.47	15.18	23.26	16.22
16	14.66	18.84	24.07	17.53

Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
18	17.02	21.20	25.69	20.41
20	19.38	22.50	27.31	21.98
22	21.27	24.07	28.73	24.07
24	23.87	26.43	30.14	25.64
26	25.29	27.48	32.17	27.21

Table A-9: Percent Damage Siding – Saltwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	3.36	2.34	4.43	6.15
6	3.36	2.34	4.43	6.15
8	3.36	2.34	4.43	6.15
10	9.37	10.68	18.59	18.89
12	9.37	10.68	18.59	18.89
14	9.37	10.68	18.59	18.89
16	15.85	16.67	30.28	30.32
18	15.85	16.67	30.28	30.32
20	15.85	16.67	30.28	30.32
22	15.85	16.67	30.28	30.32
24	22.82	23.70	35.43	40.42
26	22.82	23.70	35.43	40.42
28	22.82	23.70	35.43	40.42
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	3.84	2.73	4.65	7.03
6	3.84	2.73	4.65	7.03
8	3.84	2.73	4.65	7.03
10	9.97	10.68	18.81	19.11
12	9.97	10.68	18.81	19.11
14	9.97	10.68	18.81	19.11
16	16.21	17.84	30.42	30.32
18	16.21	17.84	30.42	30.32
20	16.21	17.84	30.42	30.32

Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
22	16.21	17.84	30.42	30.32
24	22.94	23.83	35.58	40.86
26	22.94	23.83	35.58	40.86
28	22.94	23.83	35.58	40.86
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
4	4.32	3.13	4.87	7.91
6	4.32	3.13	4.87	7.91
8	4.32	3.13	4.87	7.91
10	10.57	10.68	19.03	19.33
12	10.57	10.68	19.03	19.33
14	10.57	10.68	19.03	19.33
16	16.57	19.01	30.57	30.32
18	16.57	19.01	30.57	30.32
20	16.57	19.01	30.57	30.32
22	16.57	19.01	30.57	30.32
24	23.06	23.96	35.72	41.30
26	23.06	23.96	35.72	41.30
28	23.06	23.96	35.72	41.30

Table A-10: Percent Damage OSB Sheathing – Saltwater

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
2	0.00	0.00	4.43	0.00
4	3.36	2.34	4.43	6.15
6	3.36	2.34	4.43	6.15
8	3.36	2.34	4.43	6.15
10	9.37	10.68	18.59	18.89
12	9.37	10.68	18.59	18.89
14	9.37	10.68	18.59	18.89
16	15.85	10.68	18.59	30.32
18	15.85	16.67	30.28	30.32
20	15.85	16.67	30.28	30.32
22	15.85	16.67	30.28	30.32

Minimum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
24	22.82	23.70	35.43	40.42
26	22.82	23.70	35.43	40.42
28	22.82	23.70	35.43	40.42
Average Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	1.56	2.21	0.00
2	0.00	0.00	4.65	0.00
4	3.84	2.73	4.65	7.03
6	3.84	2.73	4.65	7.03
8	3.84	2.73	4.65	7.03
10	9.97	10.68	18.81	19.11
12	9.97	10.68	18.81	19.11
14	9.97	10.68	18.81	19.11
16	16.21	13.67	18.81	30.32
18	16.21	17.84	30.42	30.32
20	16.21	17.84	30.42	30.32
22	16.21	17.84	30.42	30.32
24	22.94	23.83	35.58	40.86
26	22.94	23.83	35.58	40.86
28	22.94	23.83	35.58	40.86
Maximum Percent Damage				
Flood Height (in)	**Wall 1**	**Wall 2**	**Wall 3**	**Wall 4**
-6	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00
0	0.00	3.13	4.43	0.00
2	0.00	0.00	4.87	0.00
4	4.32	3.13	4.87	7.91
6	4.32	3.13	4.87	7.91
8	4.32	3.13	4.87	7.91
10	10.57	10.68	19.03	19.33
12	10.57	10.68	19.03	19.33
14	10.57	10.68	19.03	19.33
16	16.57	16.67	19.03	30.32
18	16.57	19.01	30.57	30.32
20	16.57	19.01	30.57	30.32
22	16.57	19.01	30.57	30.32
24	23.06	23.96	35.72	41.30
26	23.06	23.96	35.72	41.30
28	23.06	23.96	35.72	41.30

APPENDIX B

DEPTH DAMAGE CURVES

B.1 Freshwater Flood Test Depth-Damage Curves

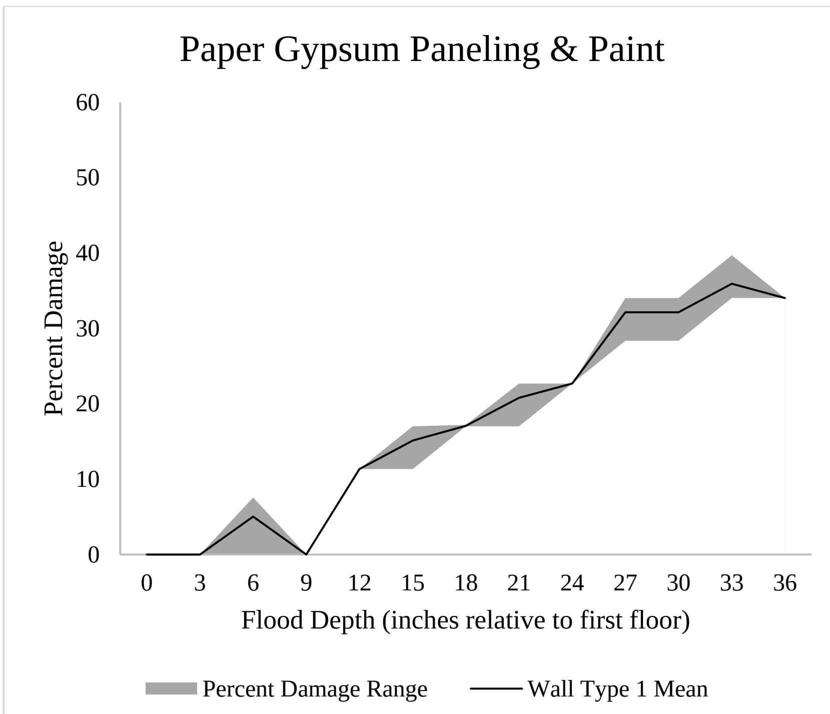

Figure B-1: Wall 1 Depth-damage Curve from Freshwater Flood Test

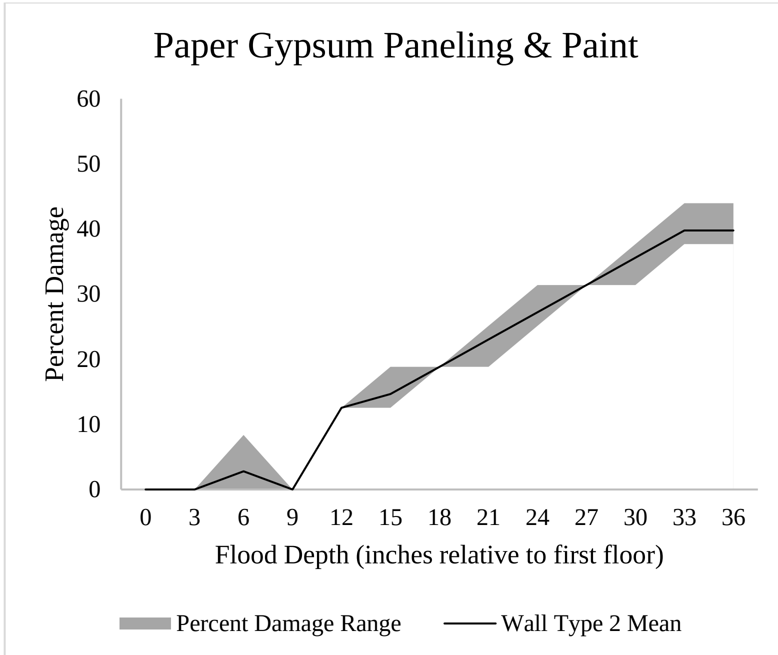

Figure B-2: Wall 2 Depth-damage Curve from Freshwater Flood Test

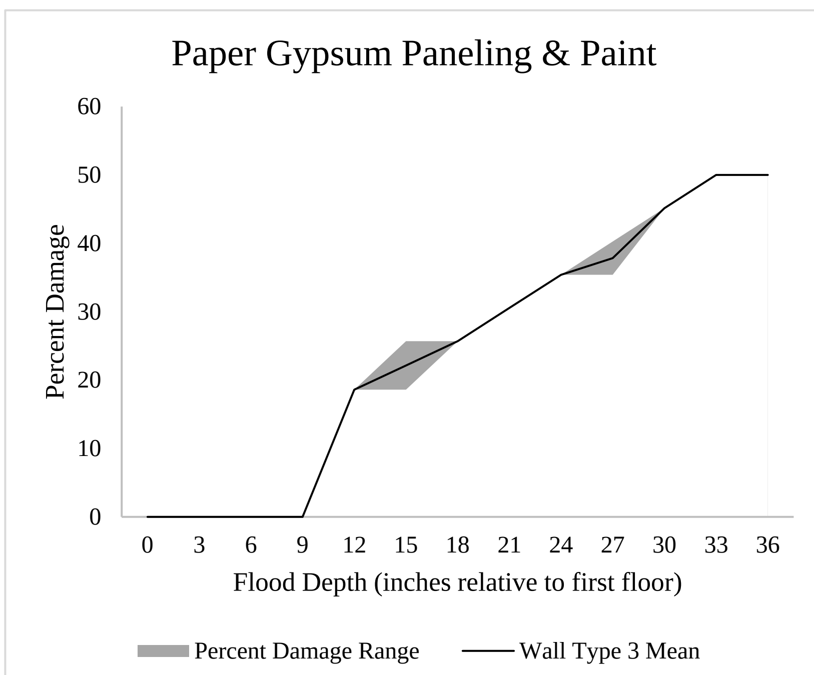

Figure B-3: Wall 3 Depth-damage Curve from Freshwater Flood Test

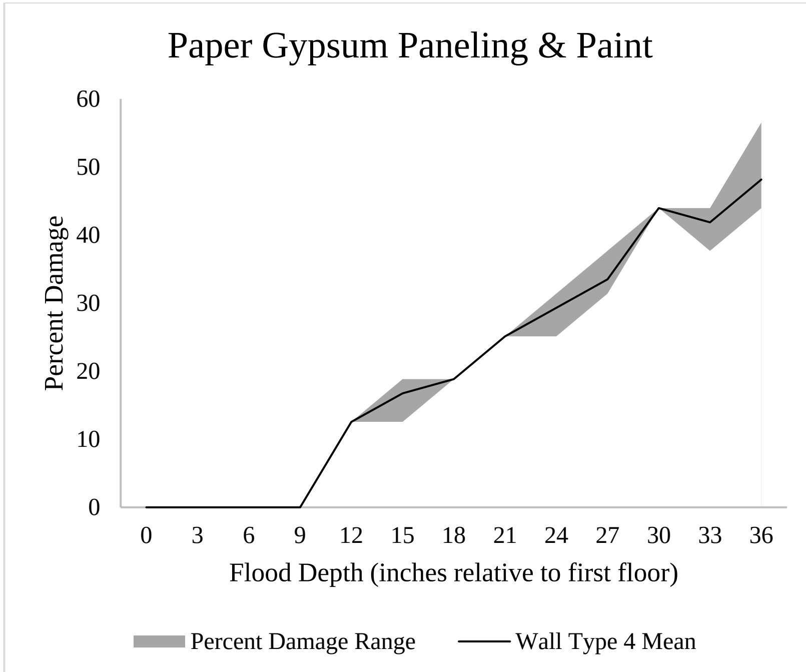

Figure B-4: Wall 4 Depth-damage Curve from Freshwater Flood Test

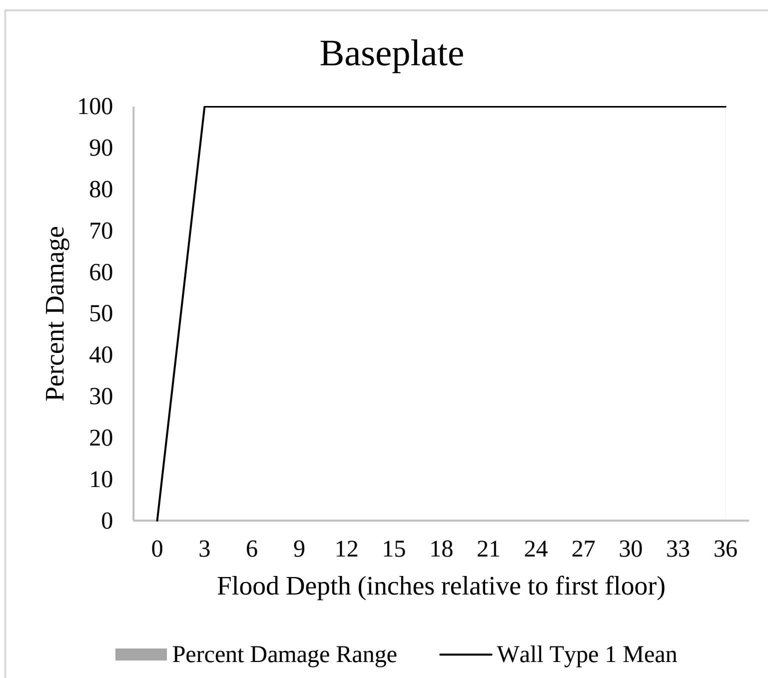

Figure B-5: Wall 1 Depth-damage Curve from Freshwater Flood Test

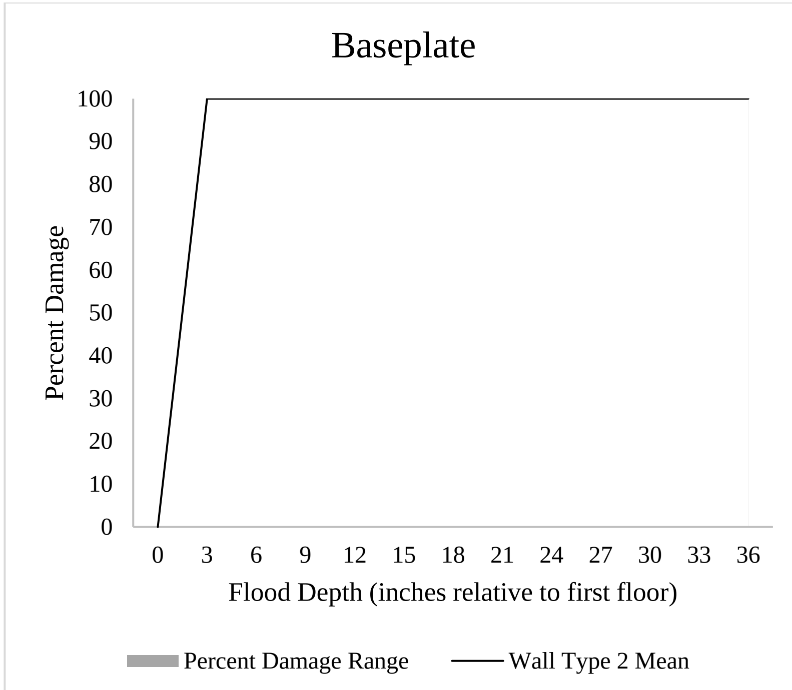

Figure B-6: Wall 2 Depth-damage Curve from Freshwater Flood Test

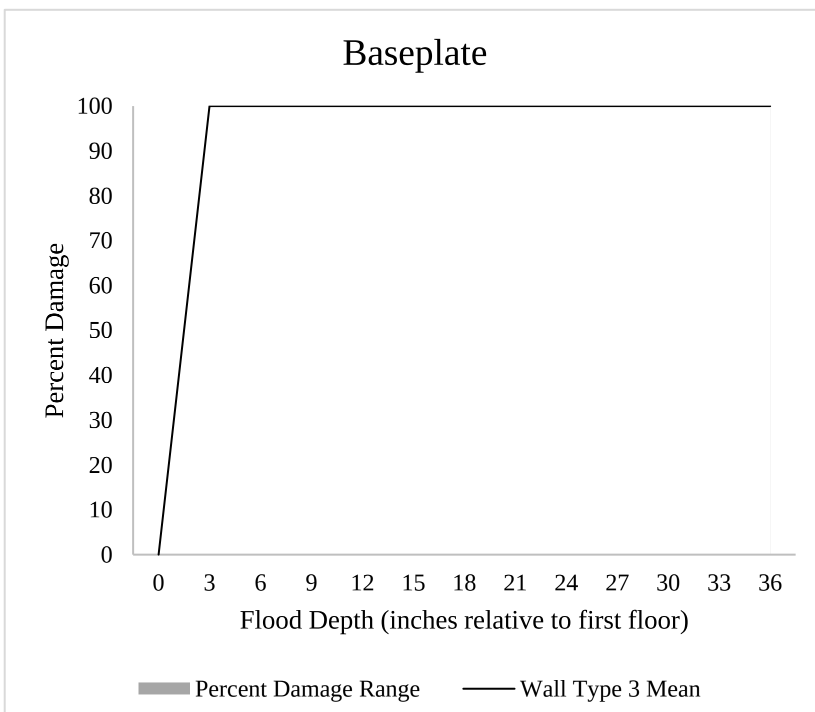

Figure B-7: Wall 3 Depth-damage Curve from Freshwater Flood Test

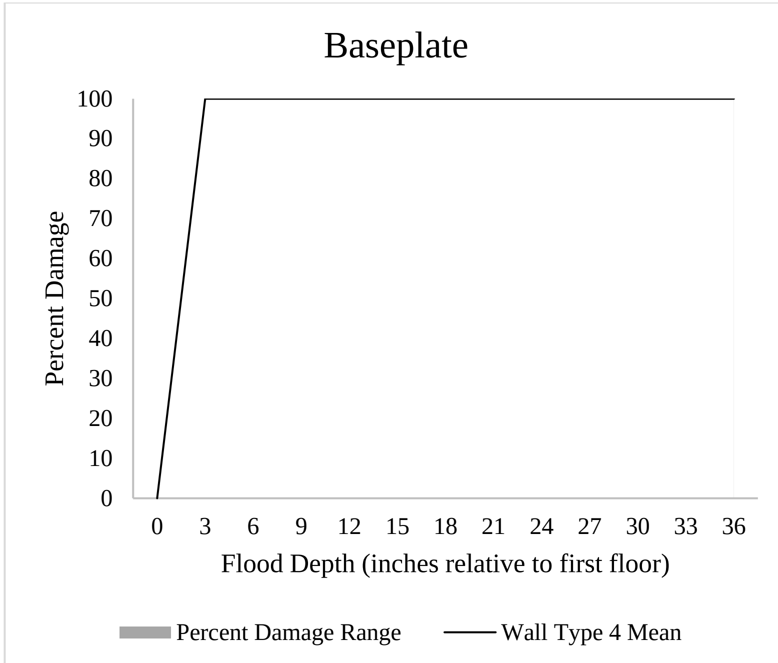

Figure B-8: Wall 4 Depth-damage Curve from Freshwater Flood Test

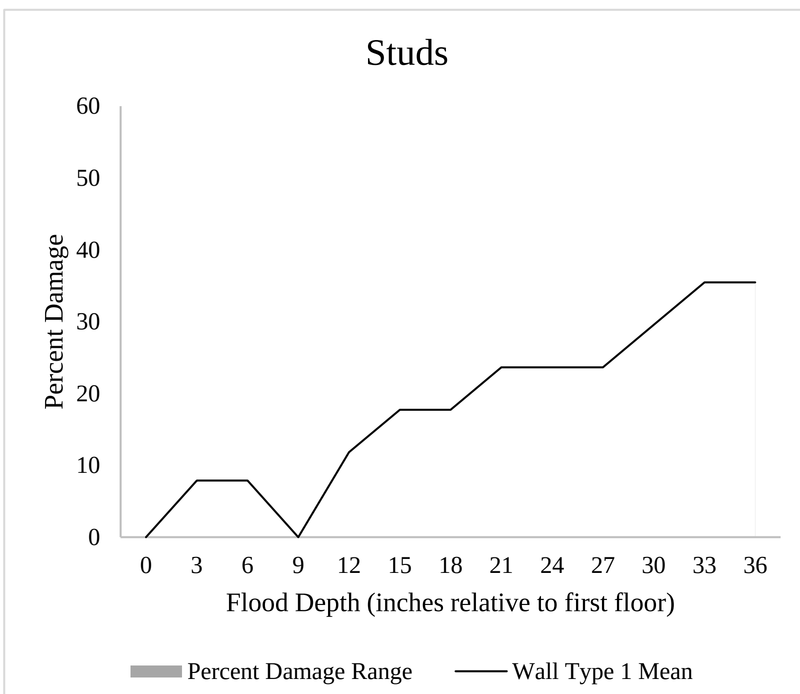

Figure B-9: Wall 1 Depth-damage Curve from Freshwater Flood Test

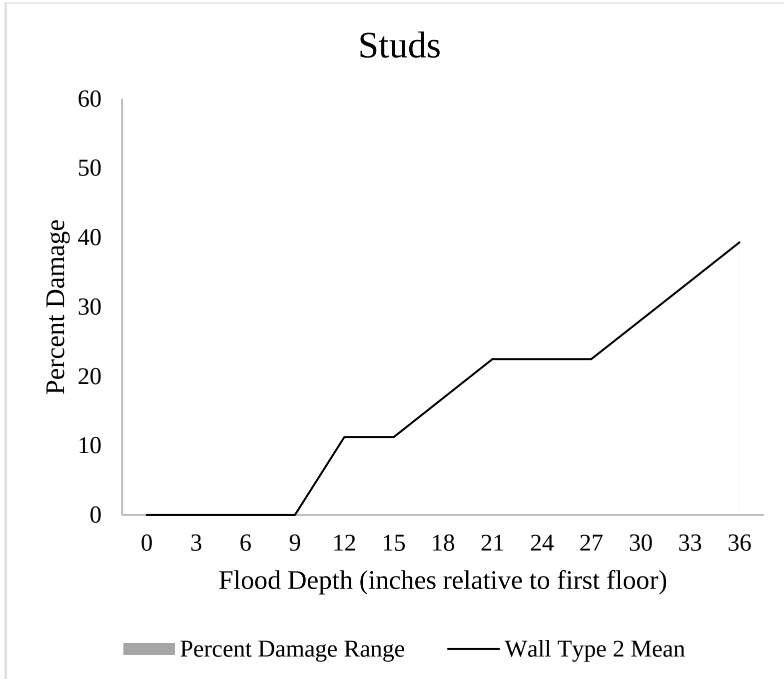

Figure B-10: Wall 2 Depth-damage Curve from Freshwater Flood Test

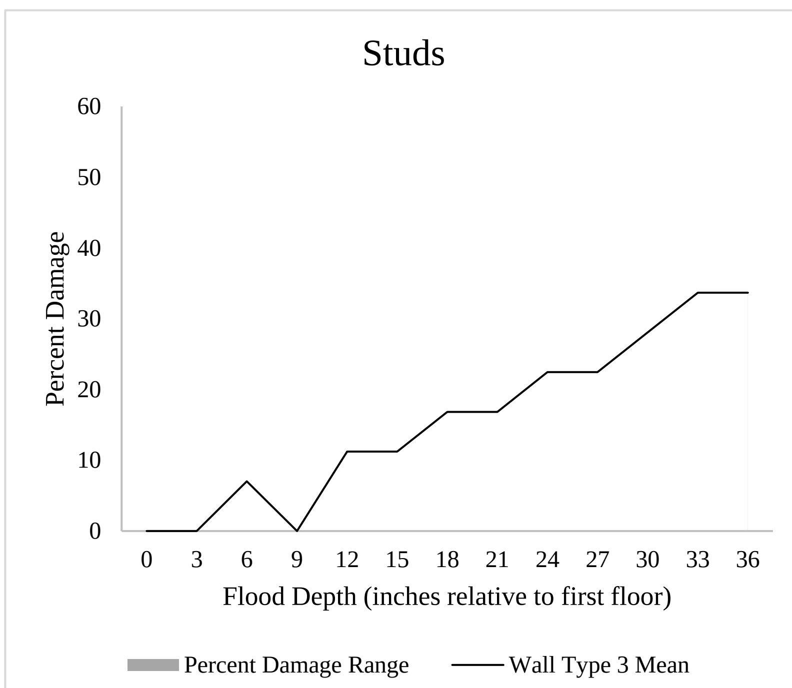

Figure B-11: Wall 3 Depth-damage Curve from Freshwater Flood Test

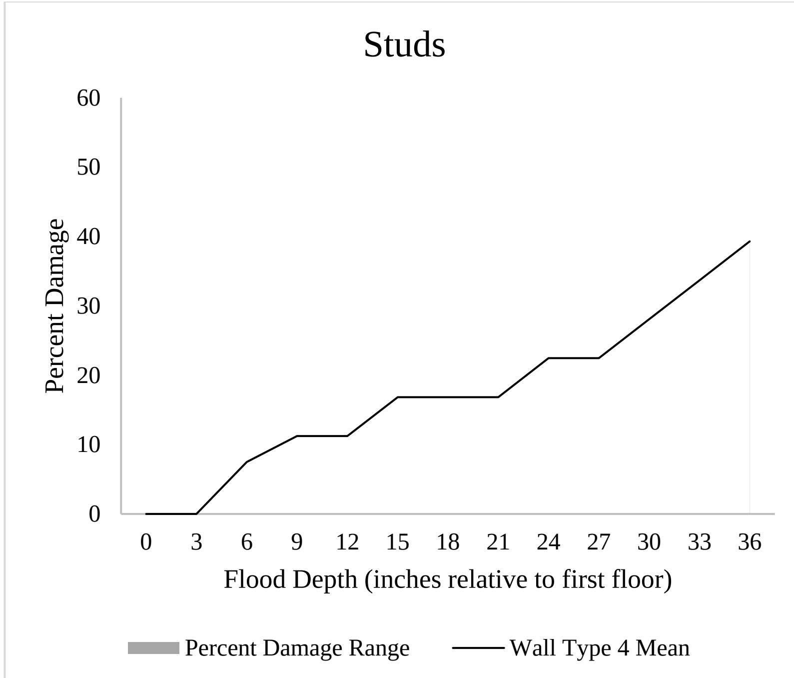

Figure B-12: Wall 4 Depth-damage Curve from Freshwater Flood Test

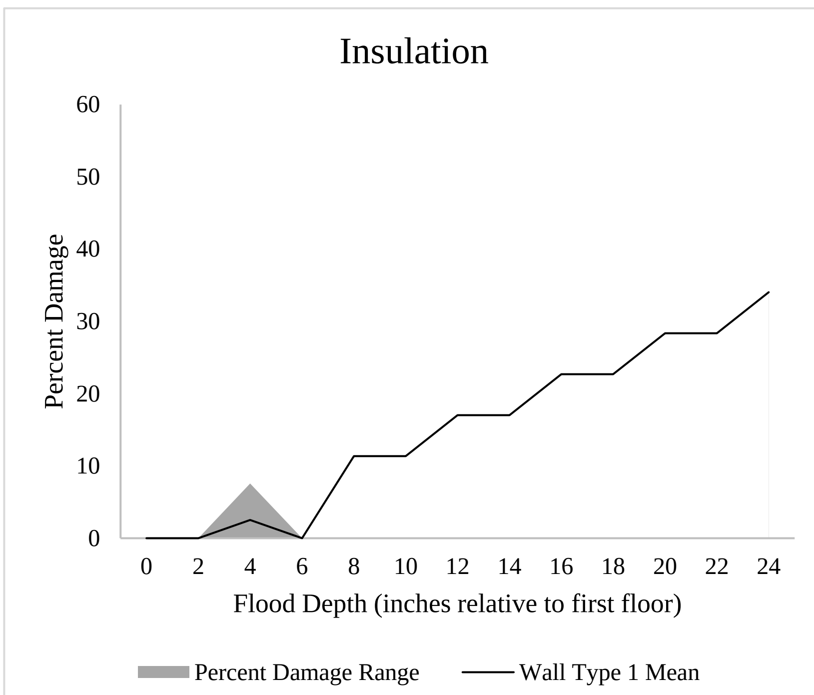

Figure B-13: Wall 1 Depth-damage Curve from Freshwater Flood Test

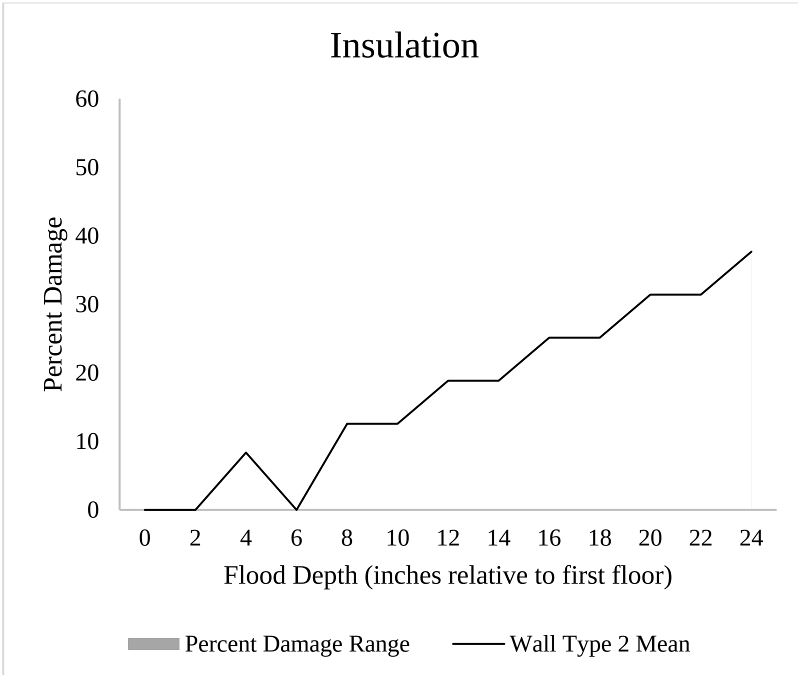

Figure B-14: Wall 2 Depth-damage Curve from Freshwater Flood Test

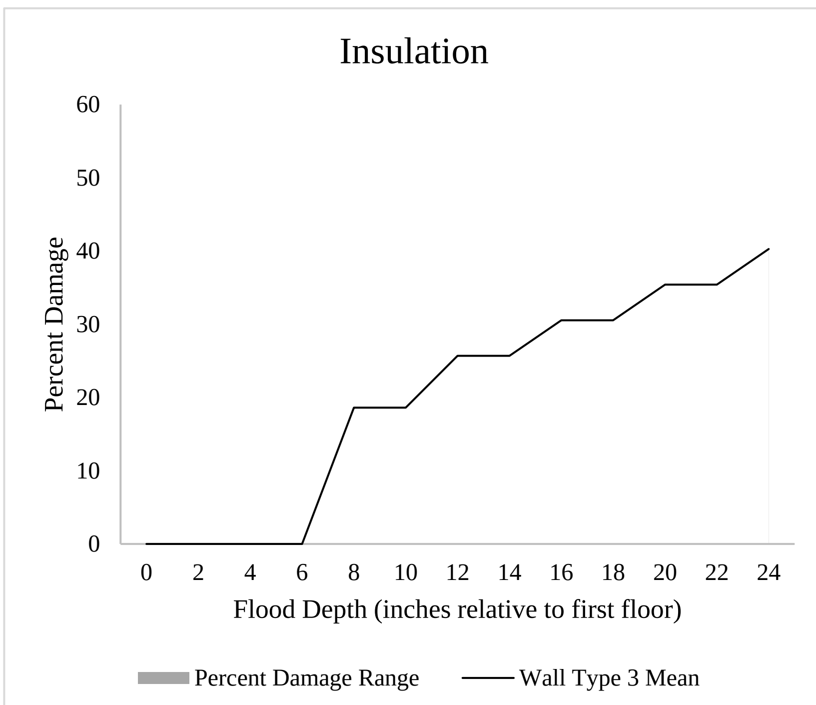

Figure B-15: Wall 3 Depth-damage Curve from Freshwater Flood Test

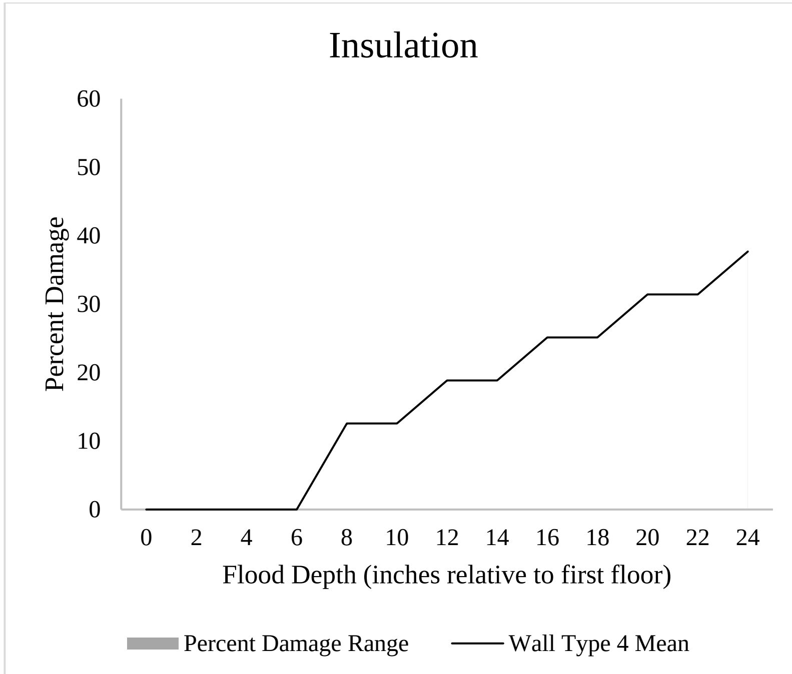

Figure B-16: Wall 4 Depth-damage Curve from Freshwater Flood Test

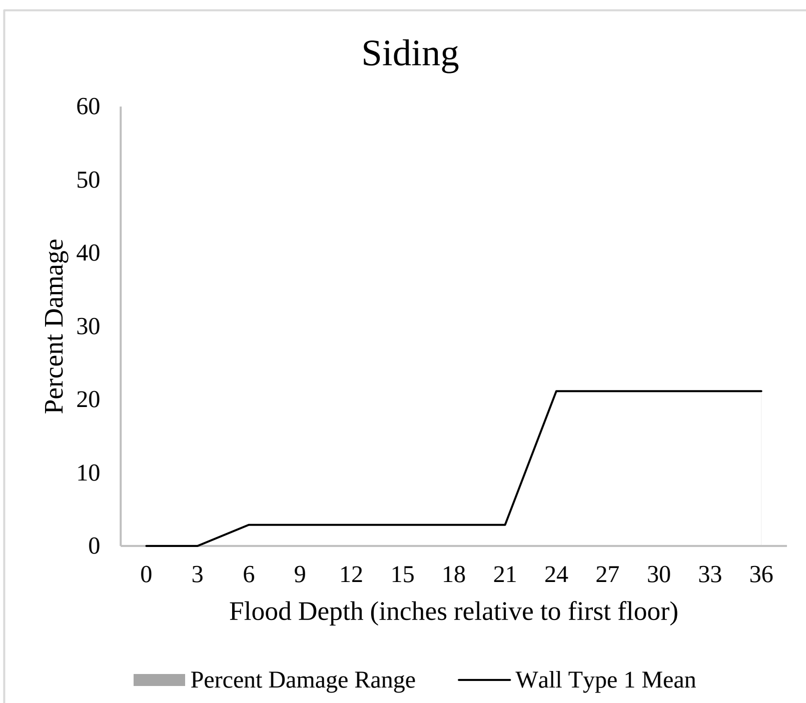

Figure B-17: Wall 1 Depth-damage Curve from Freshwater Flood Test

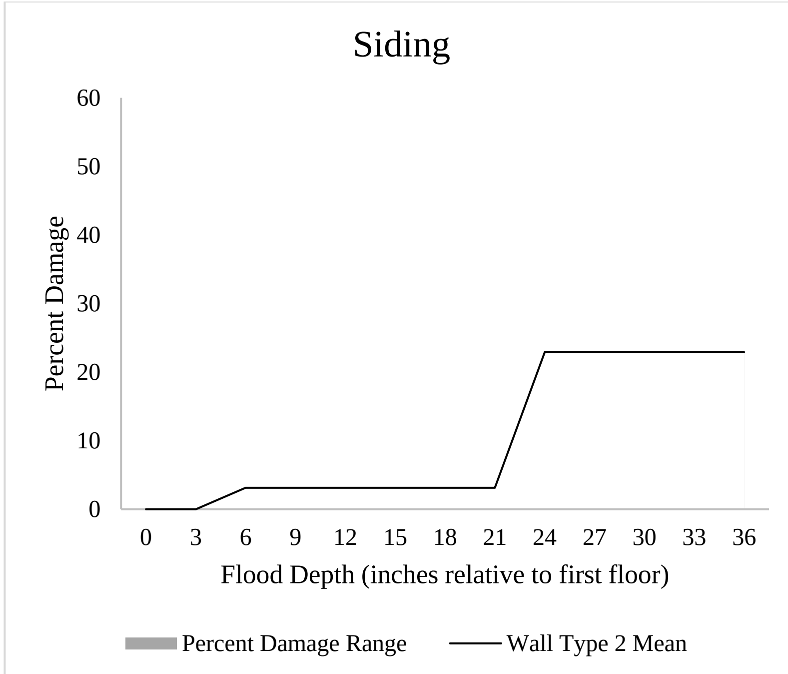

Figure B-18: Wall 2 Depth-damage Curve from Freshwater Flood Test

Figure B-19: Wall 3 Depth-damage Curve from Freshwater Flood Test

Figure B-20: Wall 4 Depth-damage Curve from Freshwater Flood Test

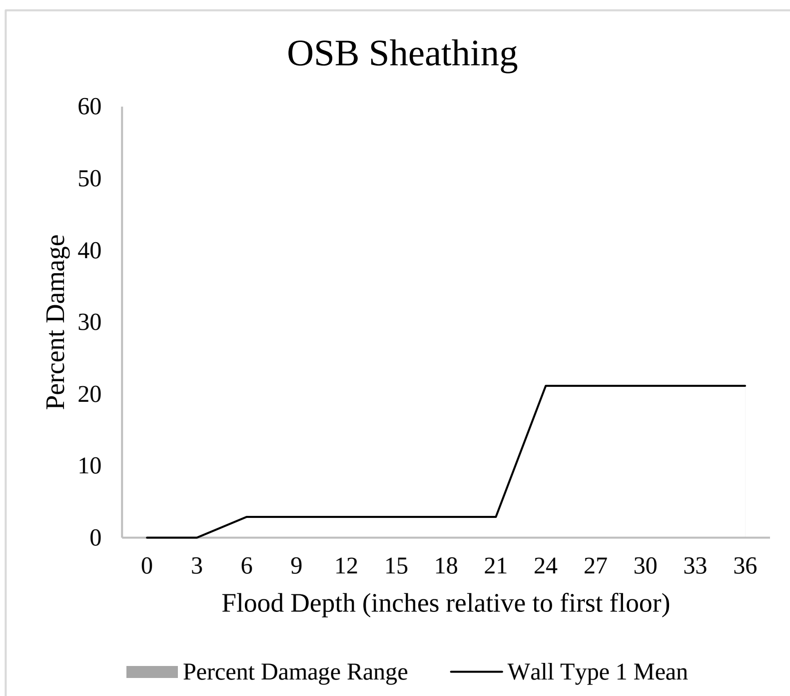

Figure B-21: Wall 1 Depth-damage Curve from Freshwater Flood Test

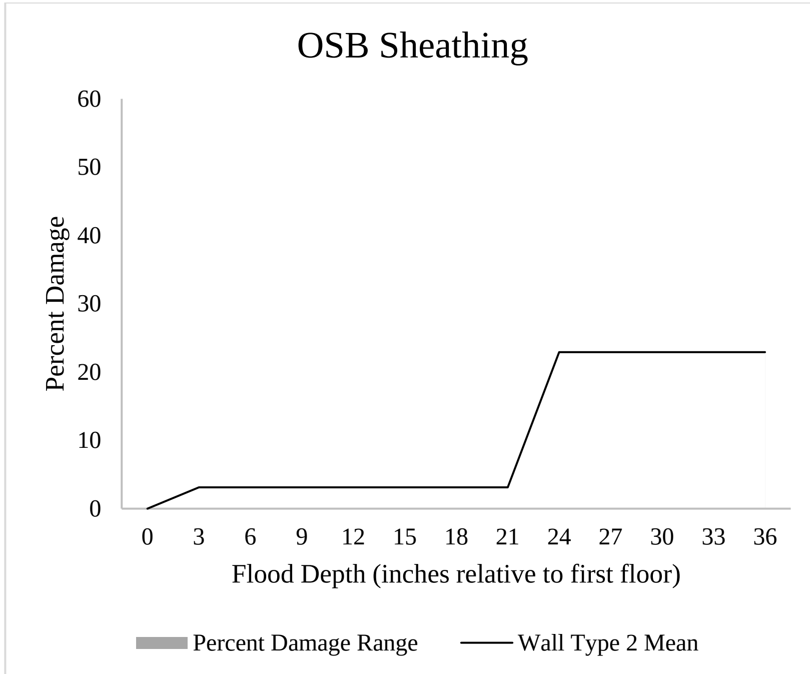

Figure B-22: Wall 2 Depth-damage Curve from Freshwater Flood Test

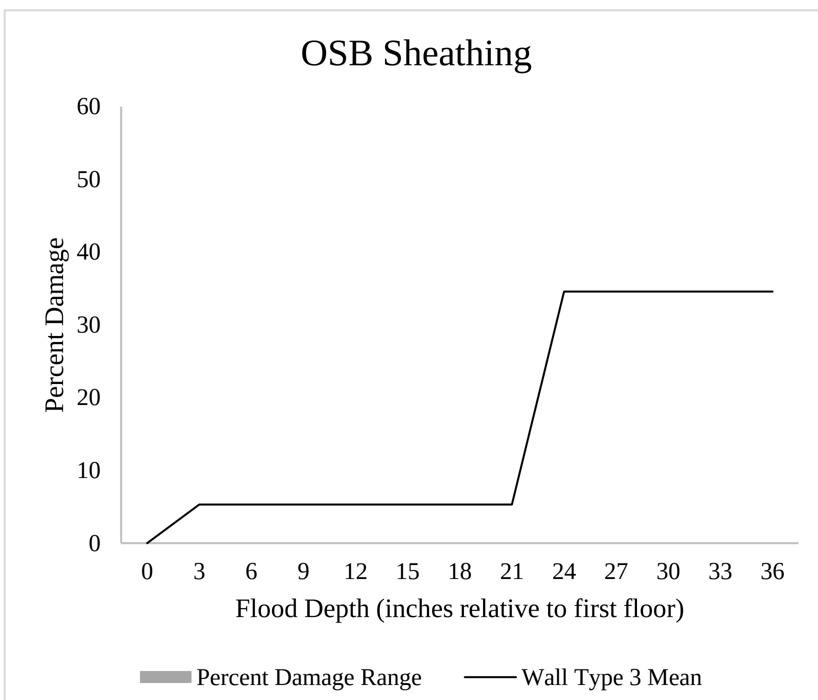

Figure B-23: Wall 3 Depth-damage Curve from Freshwater Flood Test

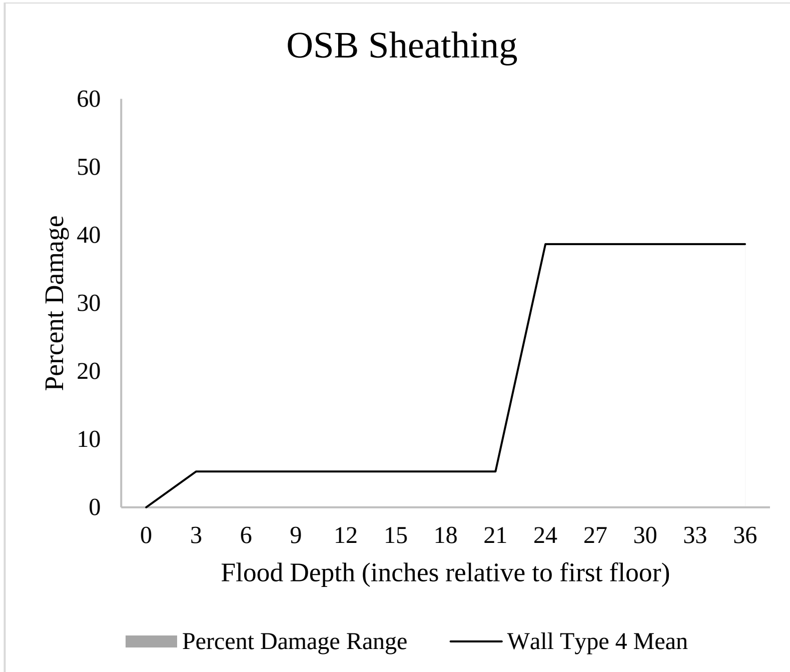

Figure B-24: Wall 4 Depth-damage Curve from Freshwater Flood Test

B.2 Freshwater Flood Test Comparison Depth-Damage Curves

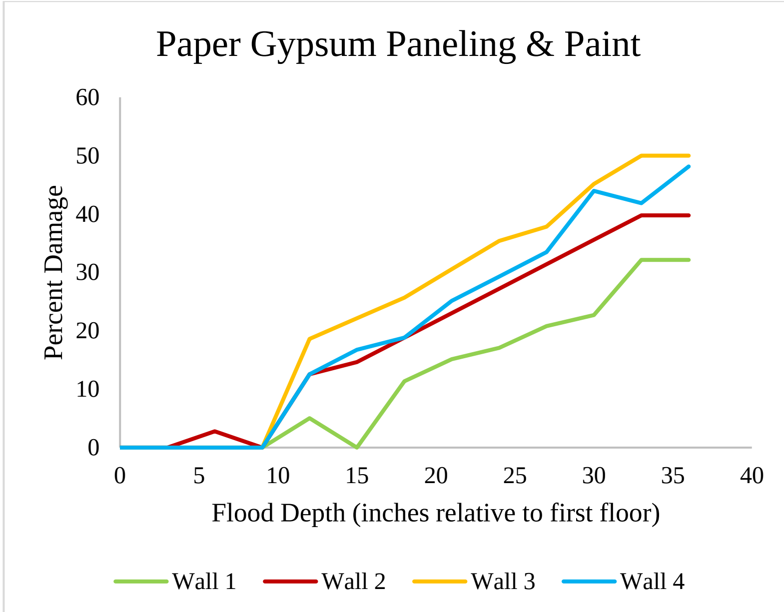

Figure B-25: Comparison of Walls 1-4 Depth-damage Curves - Freshwater

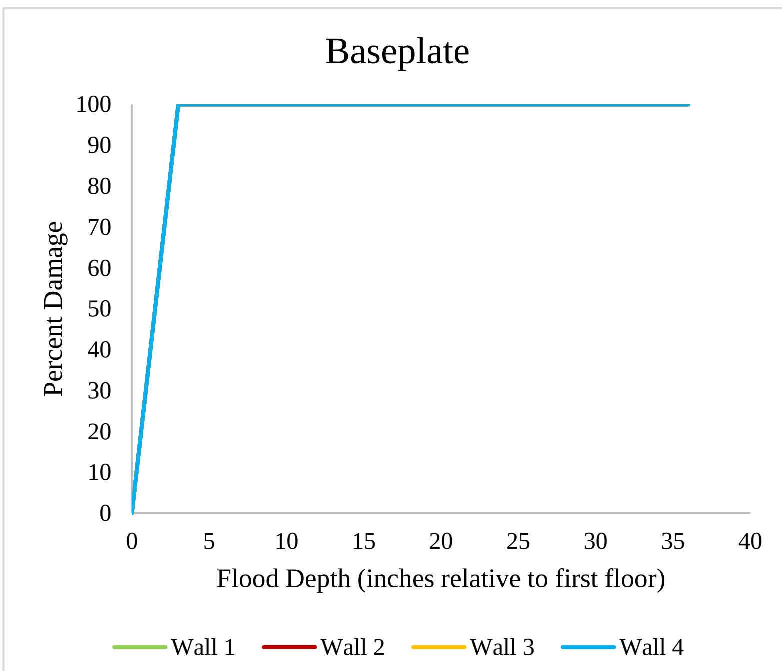

Figure B-26: Comparison of Walls 1-4 Depth-damage Curves - Freshwater

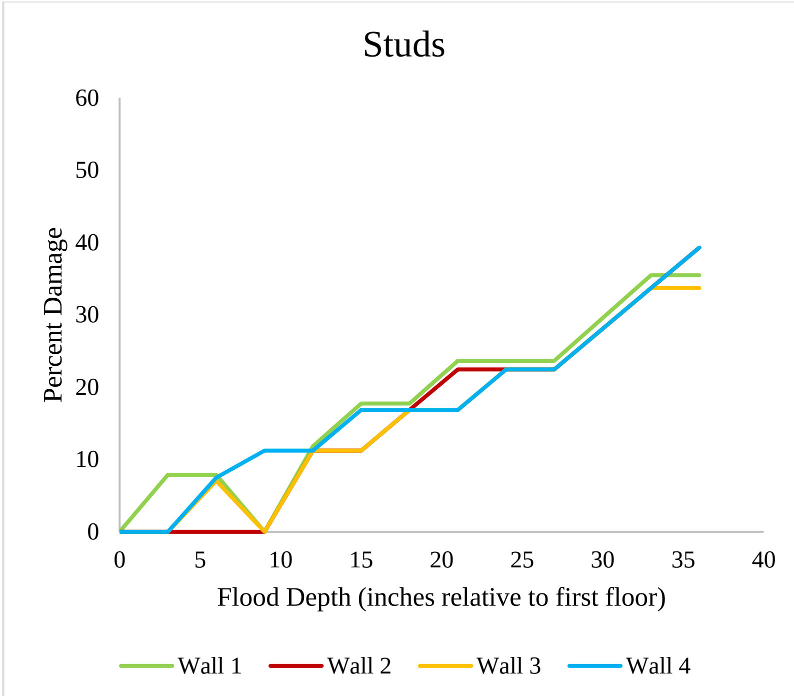

Figure B-27: Comparison of Walls 1-4 Depth-damage Curves - Freshwater

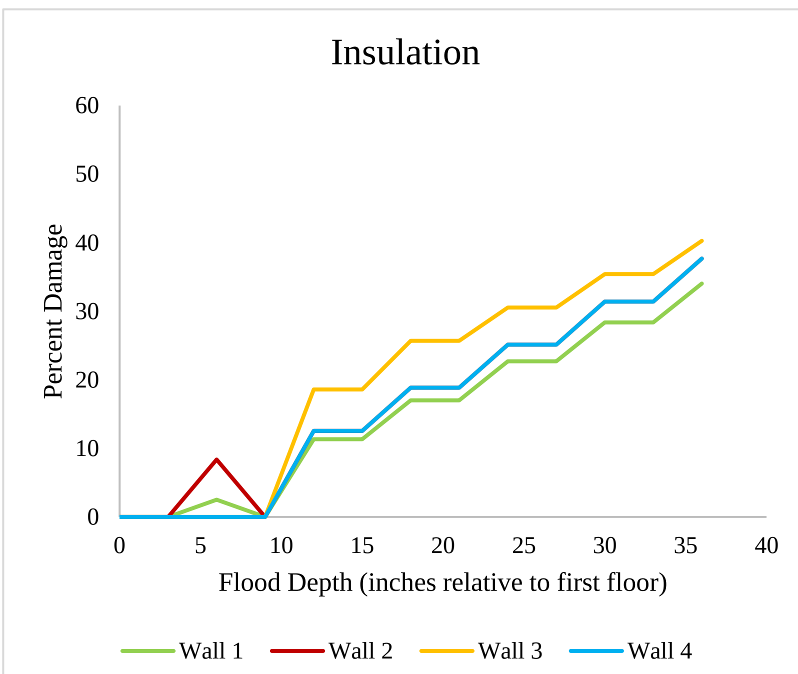

Figure B-28: Comparison of Walls 1-4 Depth-damage Curves - Freshwater

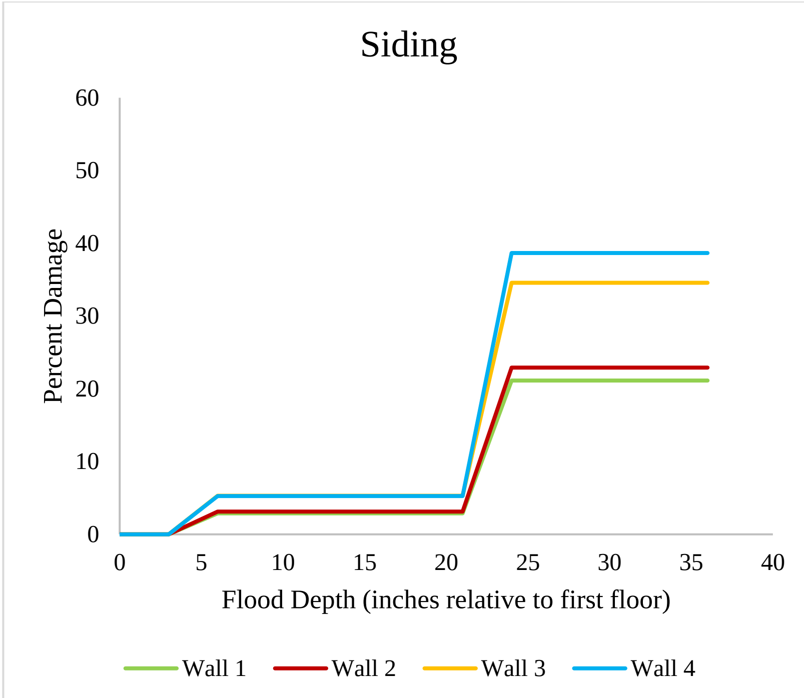

Figure B-29: Comparison of Walls 1-4 Depth-damage Curves - Freshwater

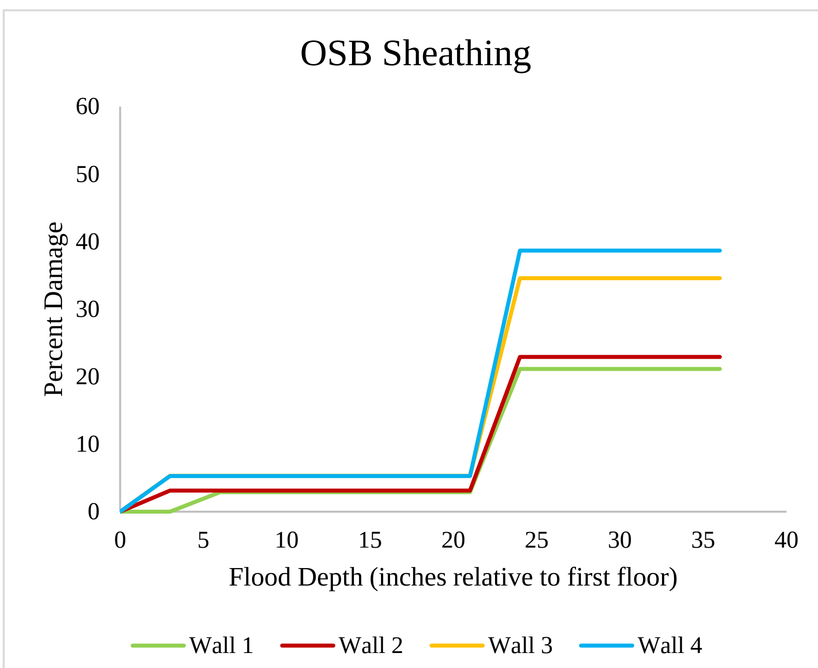

Figure B-30: Comparison of Walls 1-4 Depth-damage Curves - Freshwater

B.3 Saltwater Flood Test Depth-Damage Curves

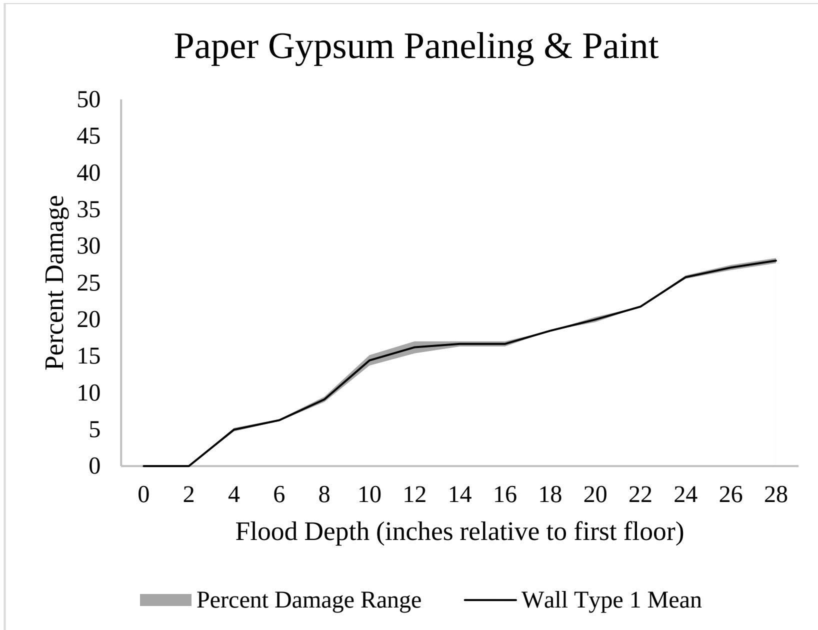

Figure B-31: Wall 1 Depth-damage Curve from Saltwater Flood Test

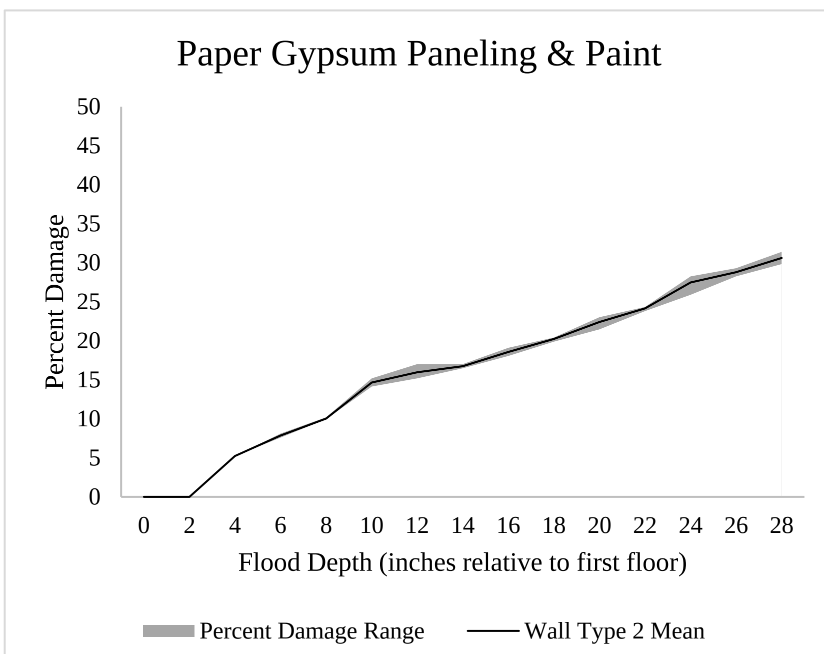

Figure B-32: Wall 2 Depth-damage Curve from Saltwater Flood Test

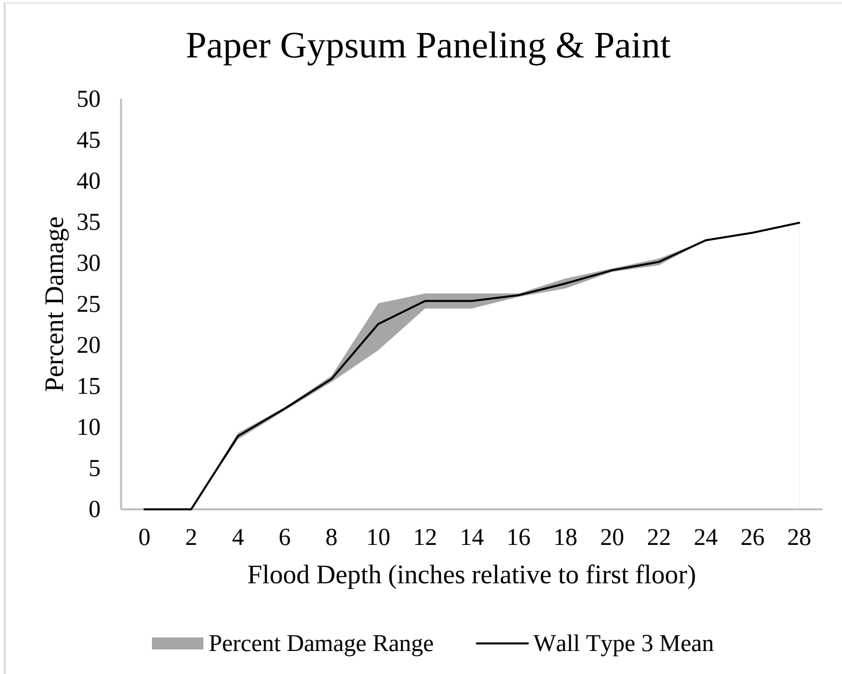

Figure B-33: Wall 3 Depth-damage Curve from Saltwater Flood Test

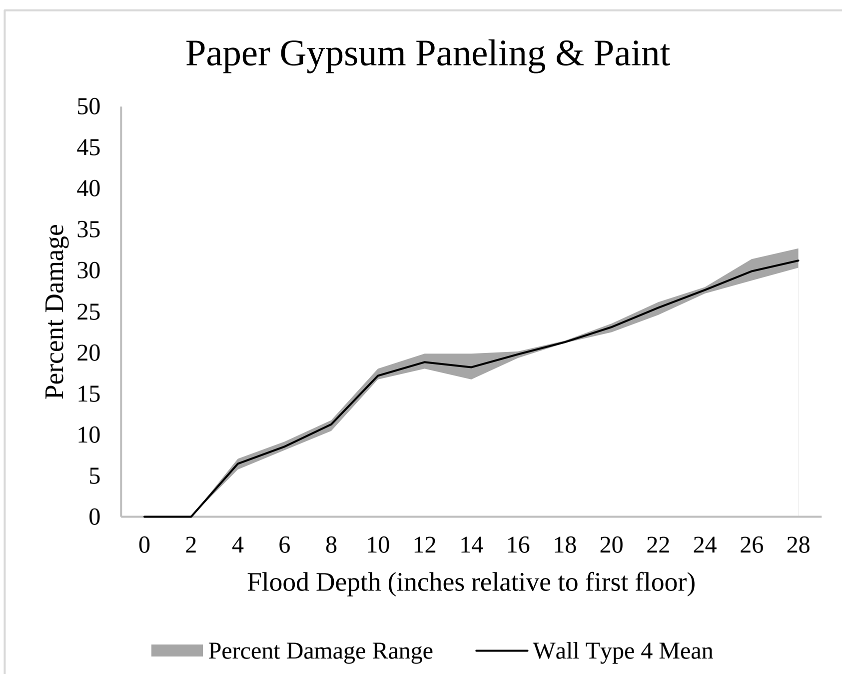

Figure B-34: Wall 4 Depth-damage Curve from Saltwater Flood Test

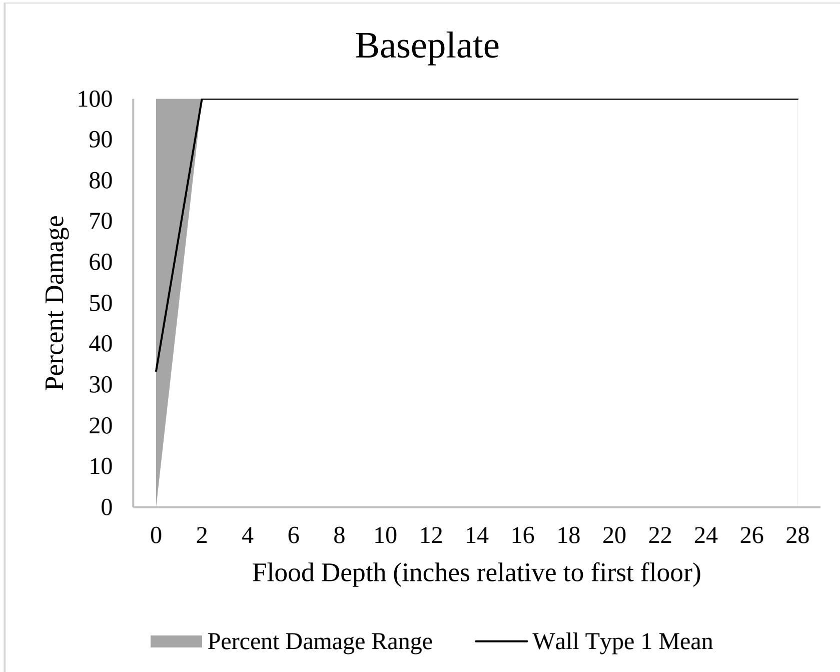

Figure B-35: Wall 1 Depth-damage Curve from Saltwater Flood Test

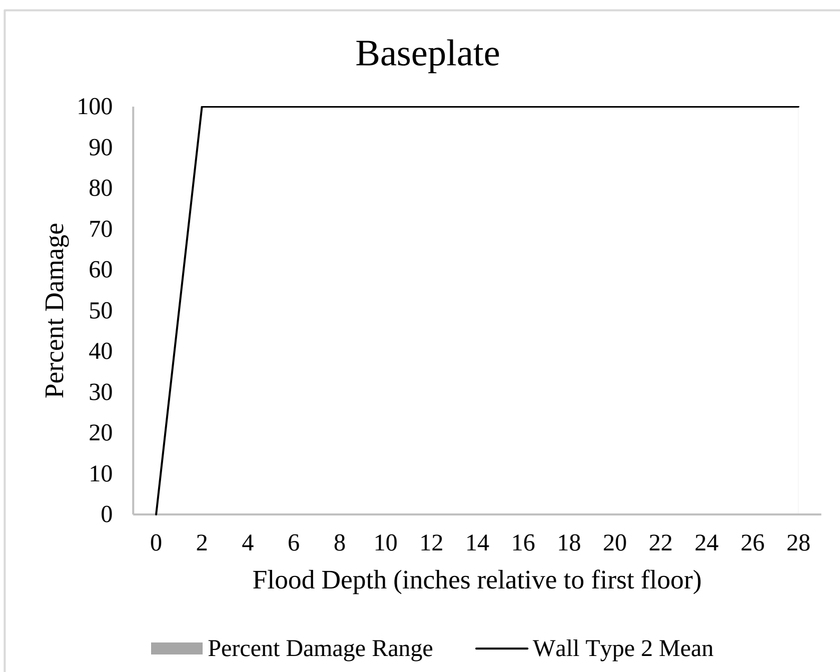

Figure B-36: Wall 2 Depth-damage Curve from Saltwater Flood Test

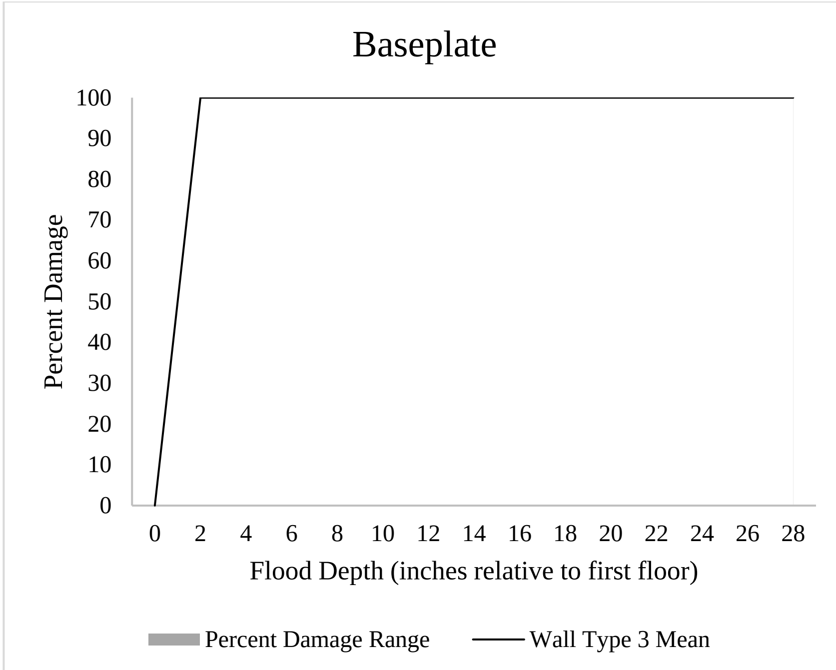

Figure B-37: Wall 3 Depth-damage Curve from Saltwater Flood Test

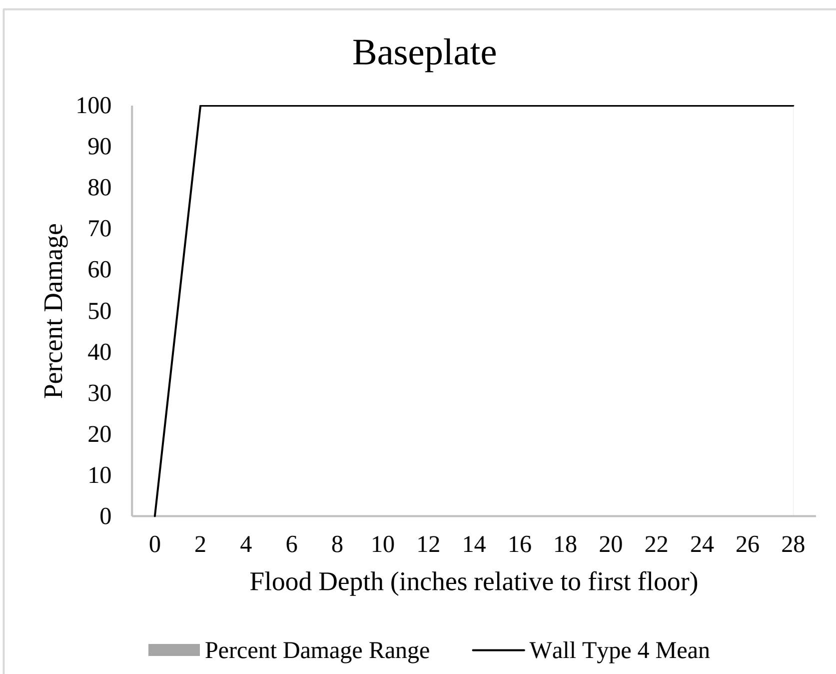

Figure B-38: Wall 4 Depth-damage Curve from Saltwater Flood Test

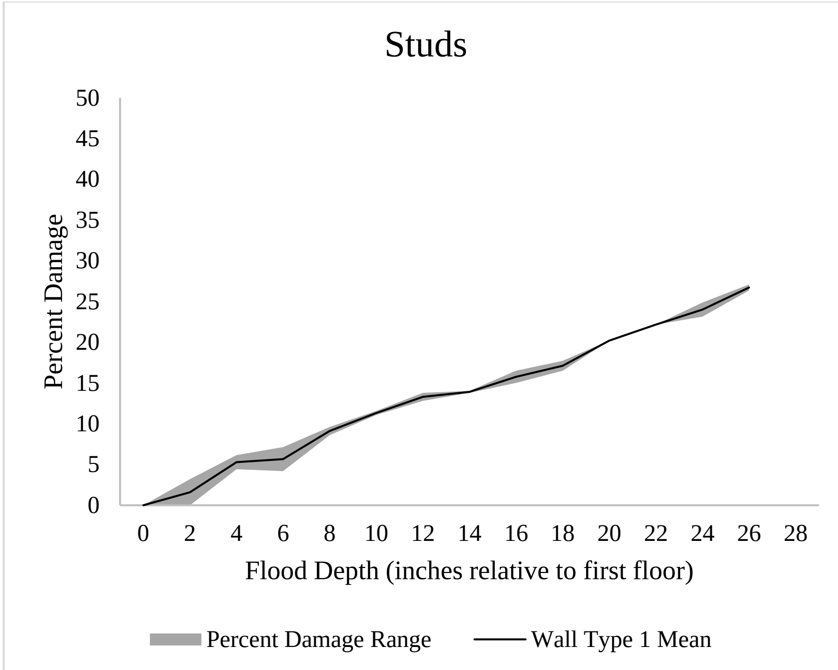

Figure B-39: Wall 1 Depth-damage Curve from Saltwater Flood Test

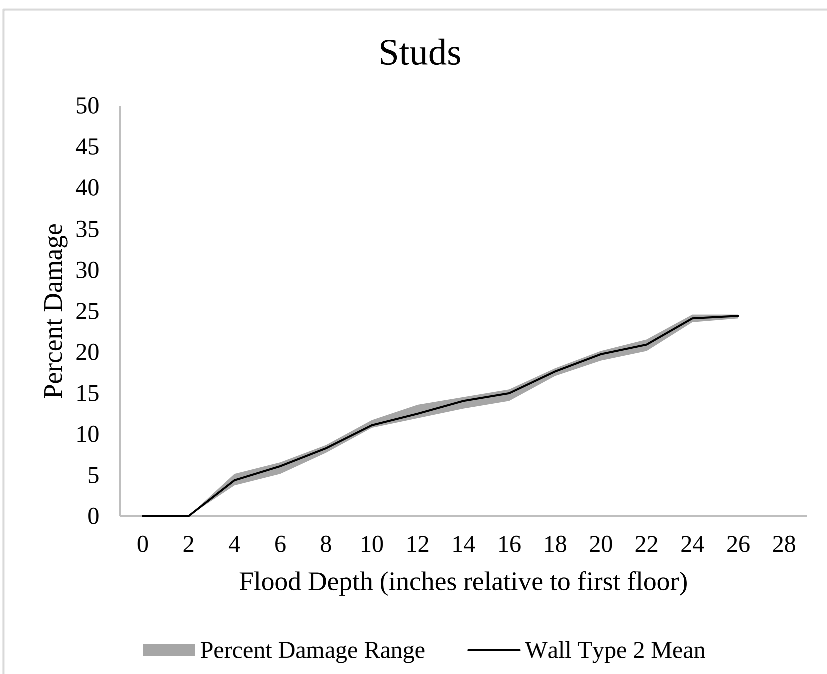

Figure B-40: Wall 2 Depth-damage Curve from Saltwater Flood Test

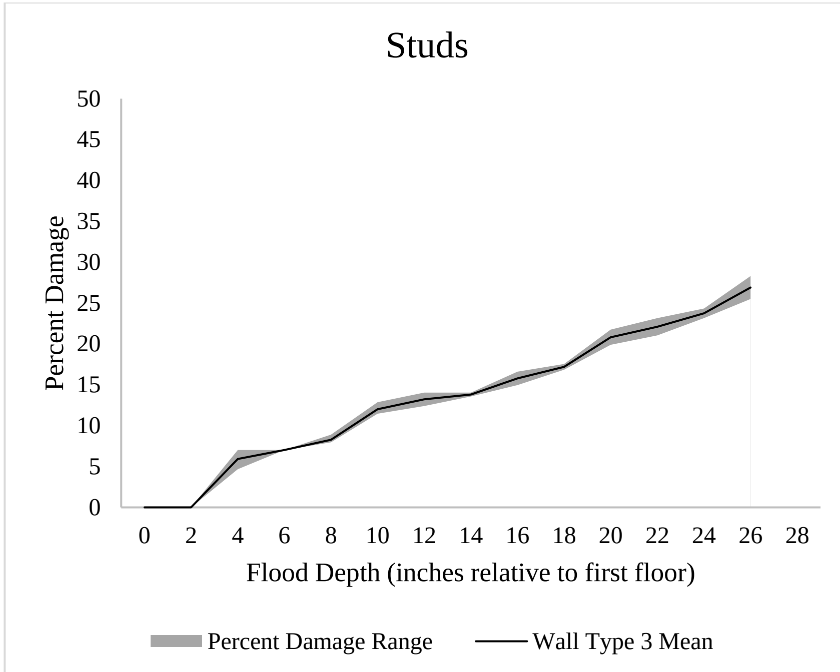

Figure B-41: Wall 3 Depth-damage Curve from Saltwater Flood Test

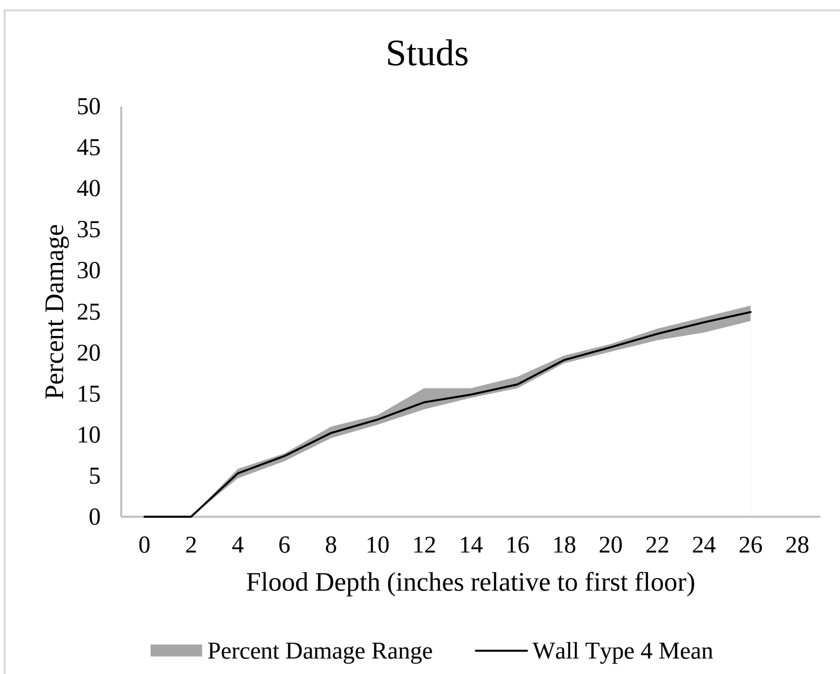

Figure B-42: Wall 4 Depth-damage Curve from Saltwater Flood Test

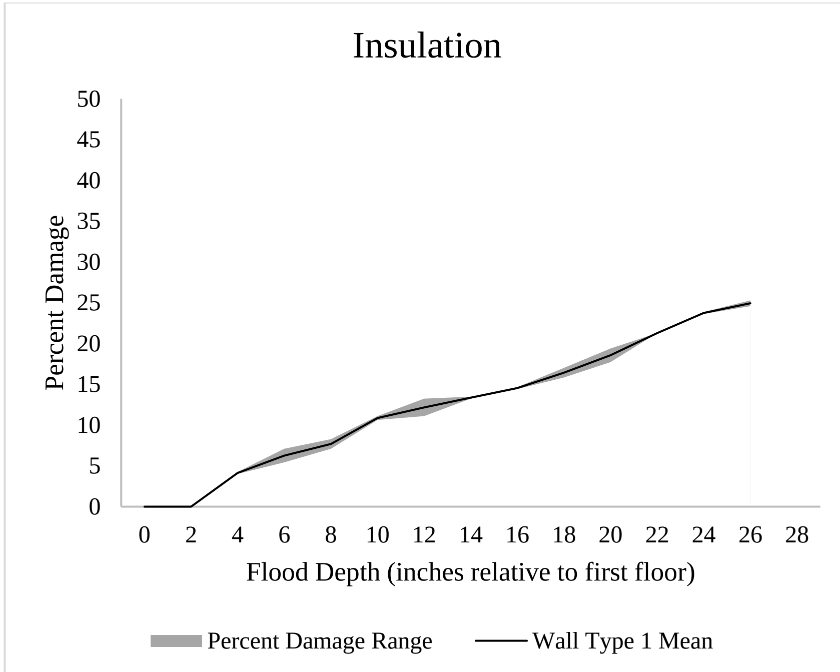

Figure B-43: Wall 1 Depth-damage Curve from Saltwater Flood Test

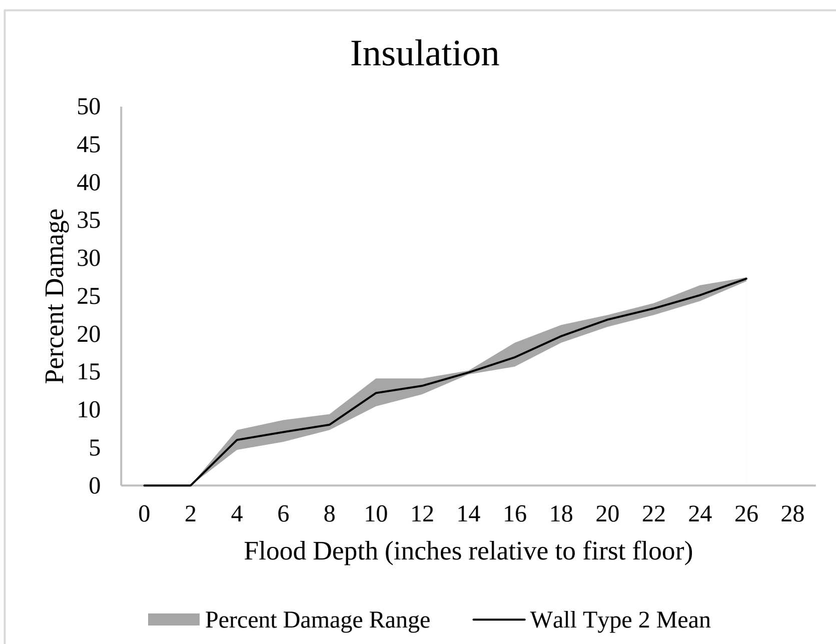

Figure B-44: Wall 2 Depth-damage Curve from Saltwater Flood Test

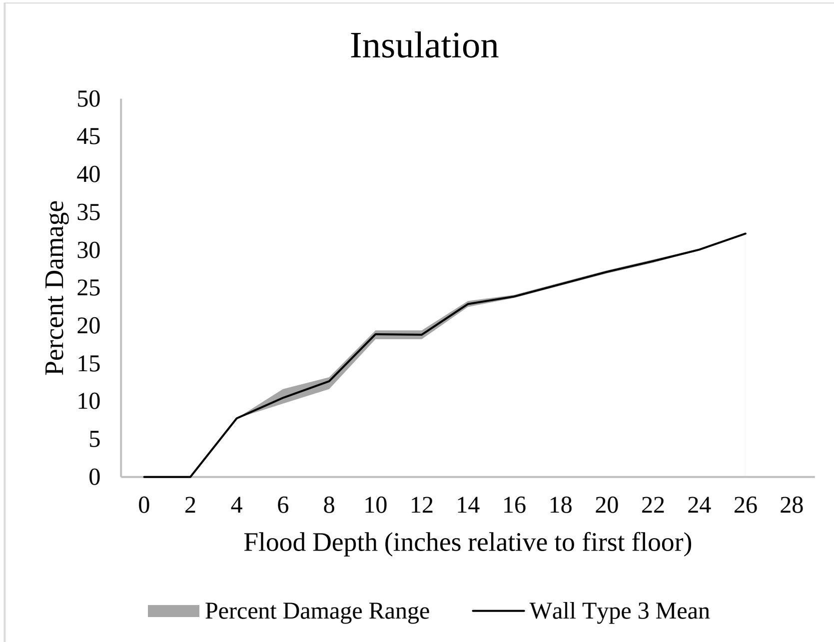

Figure B-45: Wall 3 Depth-damage Curve from Saltwater Flood Test

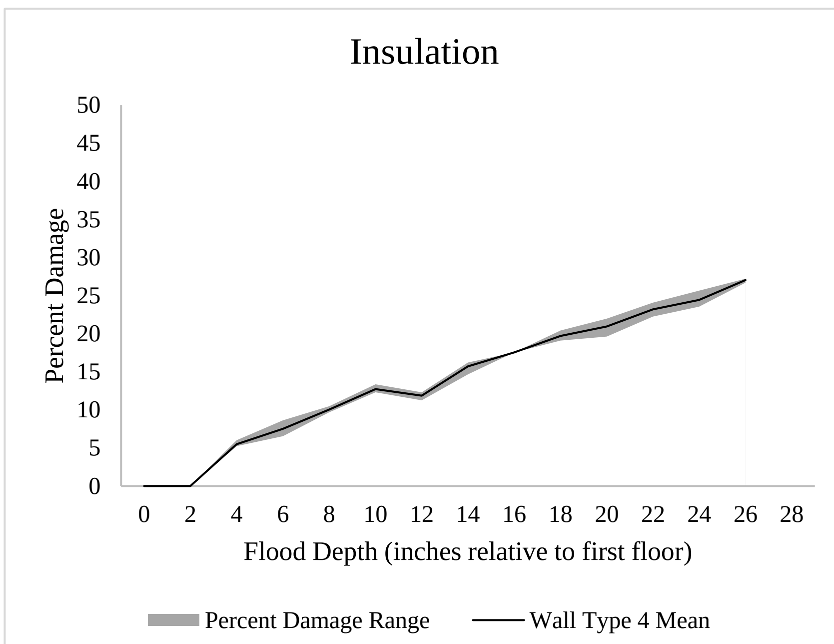

Figure B-46: Wall 4 Depth-damage Curve from Saltwater Flood Test

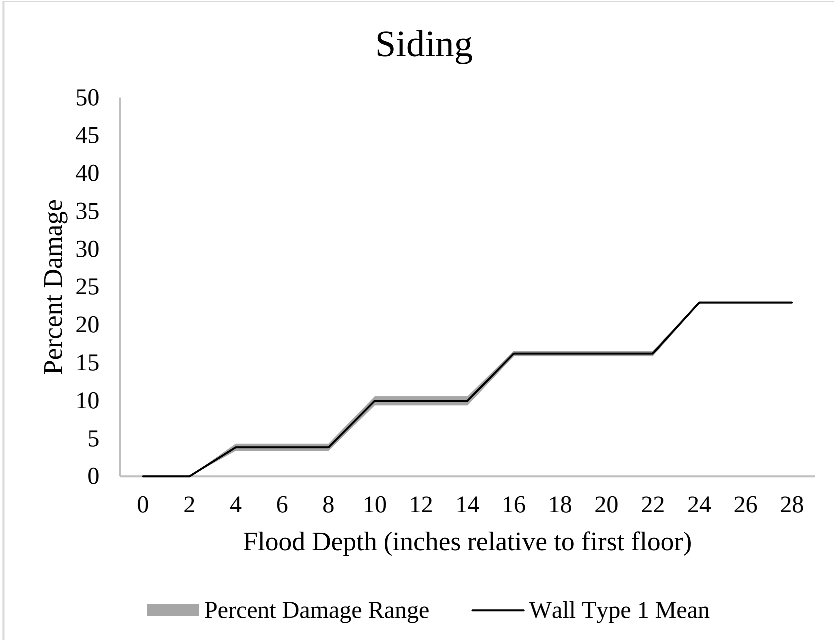

Figure B-47: Wall 1 Depth-damage Curve from Saltwater Flood Test

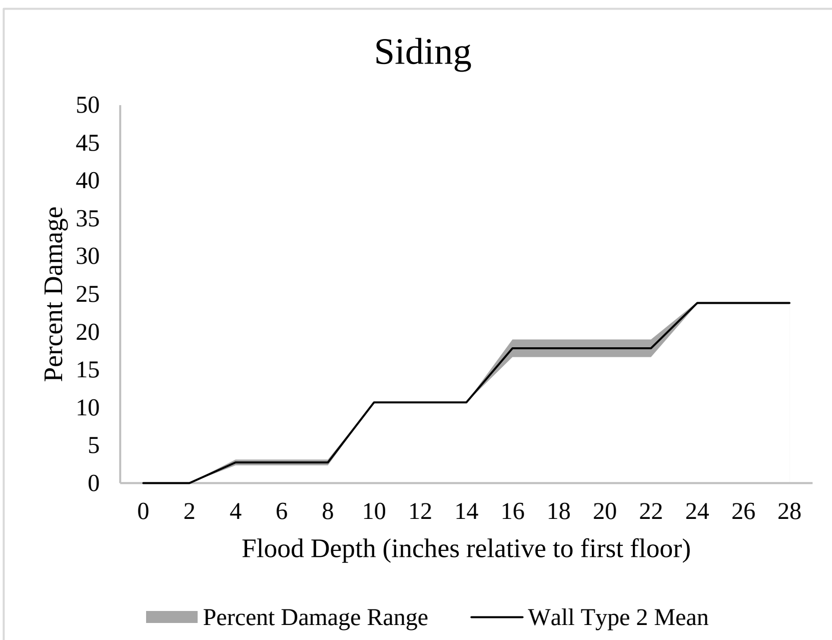

Figure B-48: Wall 2 Depth-damage Curve from Saltwater Flood Test

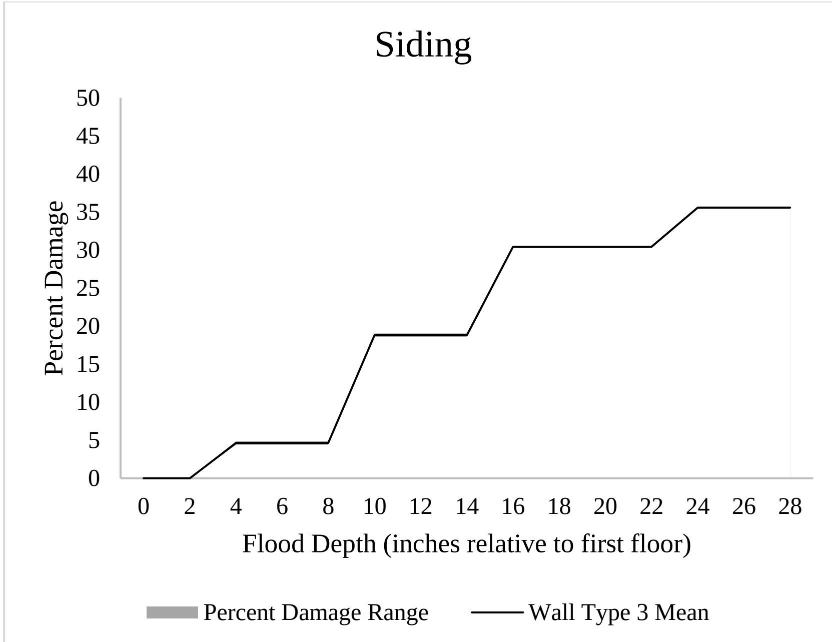

Figure B-49: Wall 3 Depth-damage Curve from Saltwater Flood Test

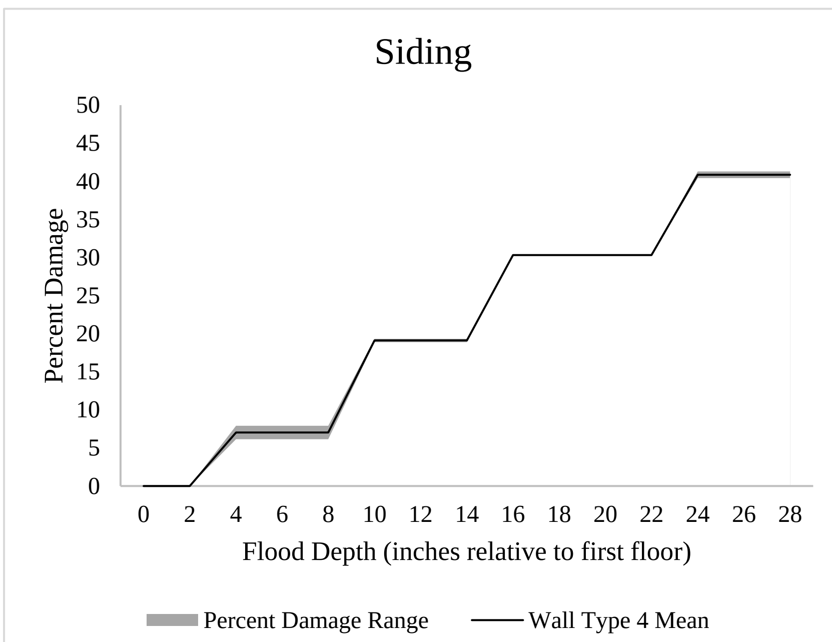

Figure B-50: Wall 4 Depth-damage Curve from Saltwater Flood Test

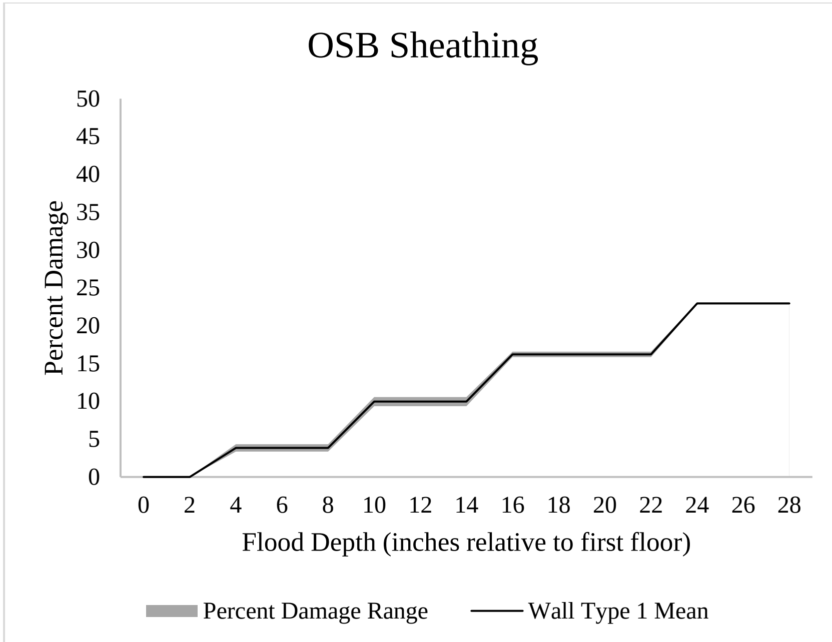

Figure B-51: Wall 1 Depth-damage Curve from Saltwater Flood Test

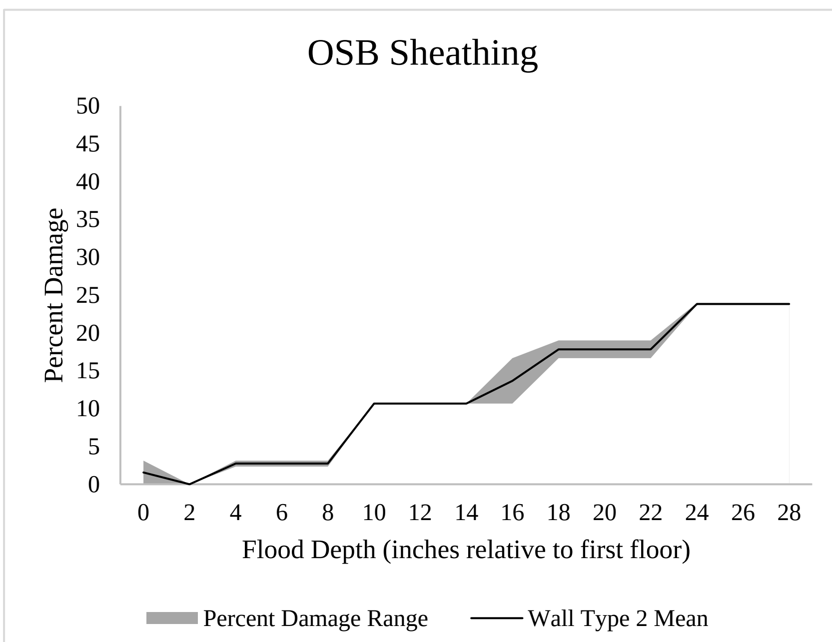

Figure B-52: Wall 2 Depth-damage Curve from Saltwater Flood Test

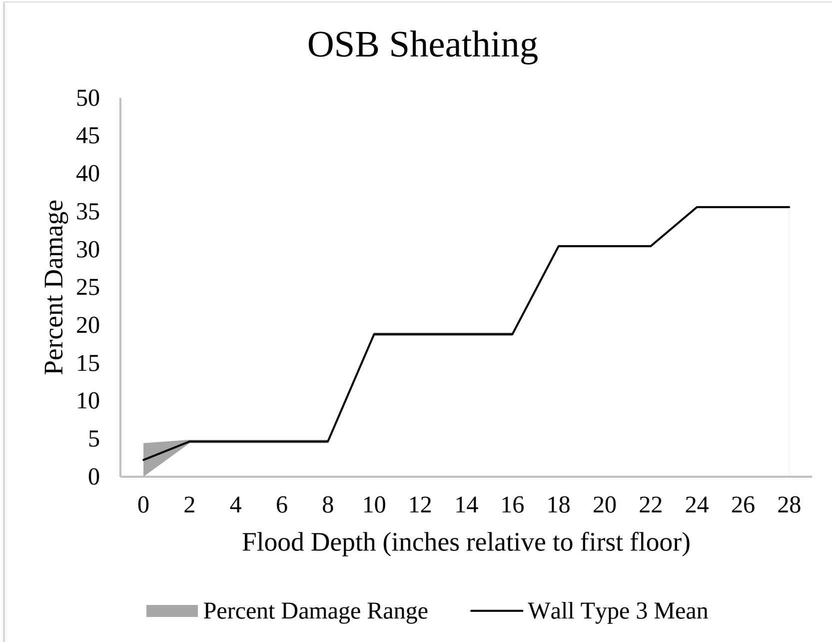

Figure B-53: Wall 3 Depth-damage Curve from Saltwater Flood Test

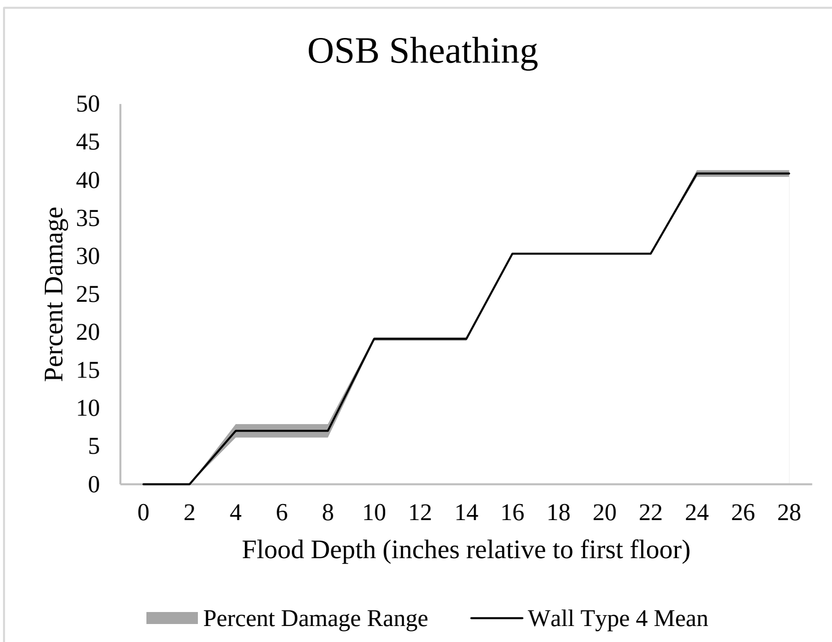

Figure B-54: Wall 4 Depth-damage Curve from Saltwater Flood Test

B.4 Saltwater Flood Test Comparison Depth-Damage Curves

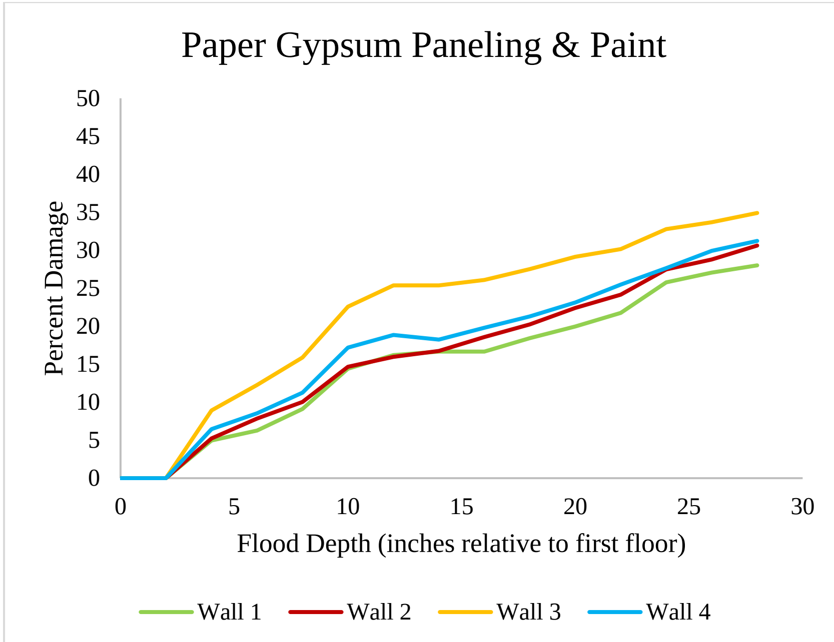

Figure B-55: Comparison of Walls 1-4 Depth-damage Curves - Saltwater

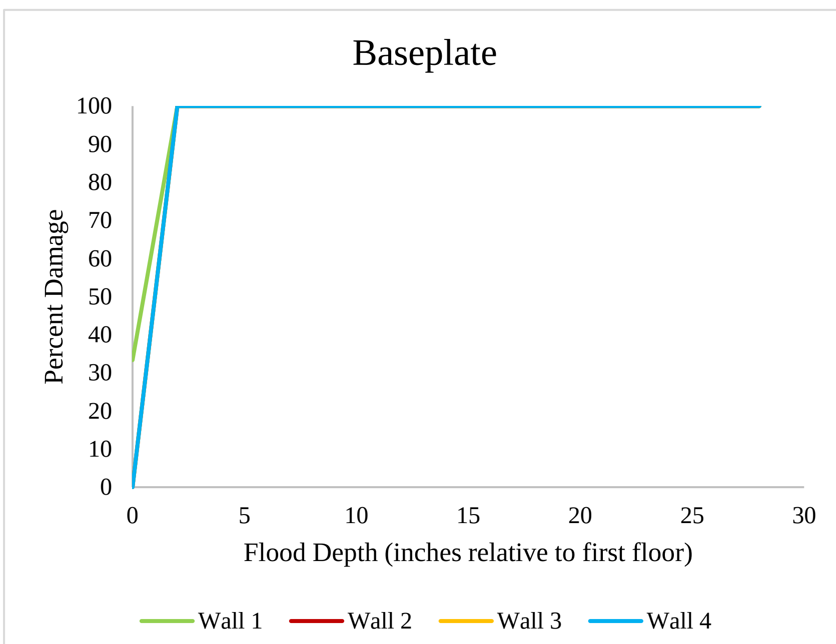

Figure B-56: Comparison of Walls 1-4 Depth-damage Curves - Saltwater

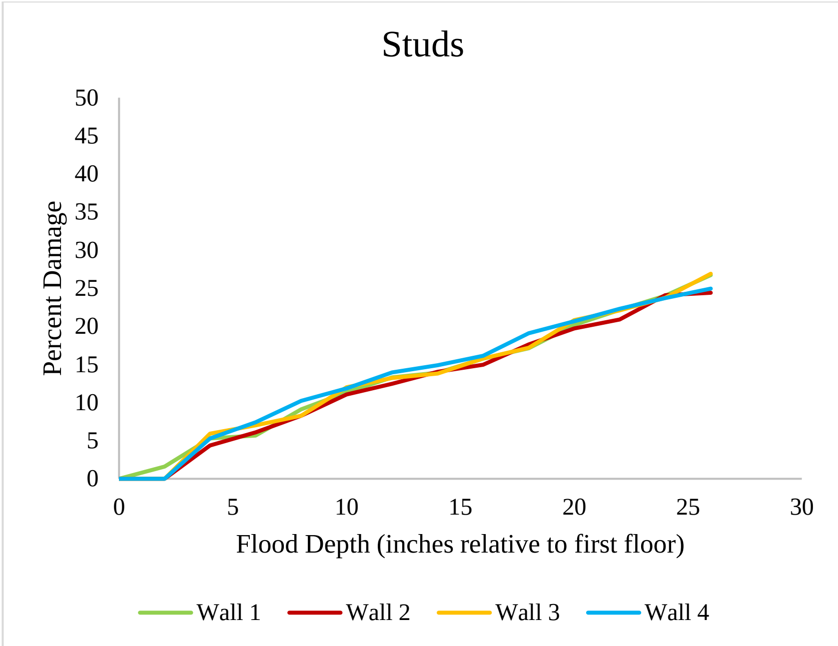

Figure B-57: Comparison of Walls 1-4 Depth-damage Curves - Saltwater

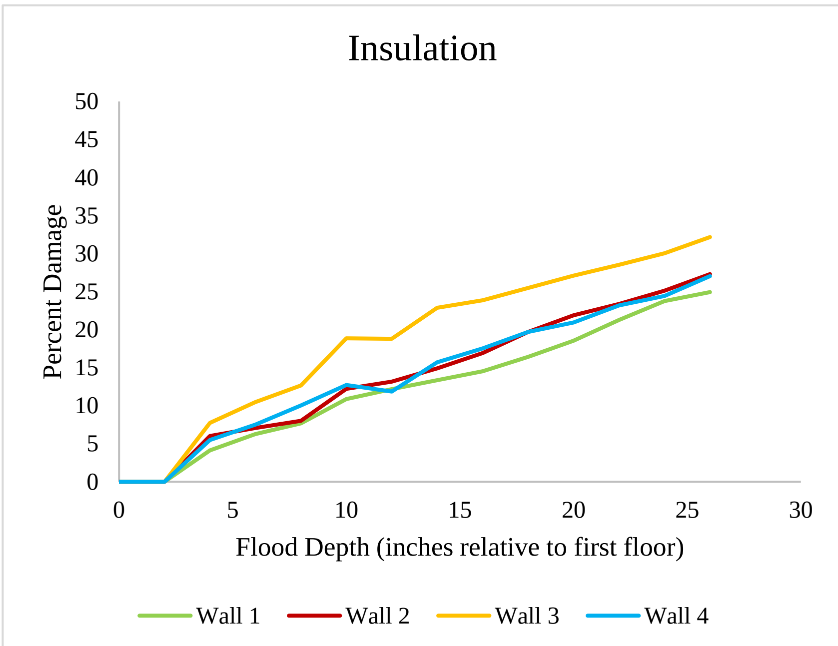

Figure B-58: Comparison of Walls 1-4 Depth-damage Curves - Saltwater

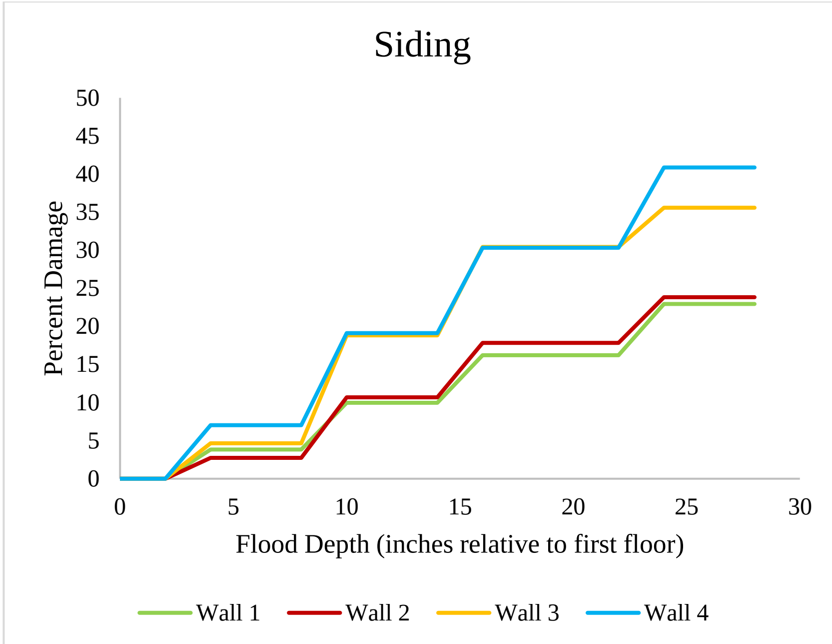

Figure B-59: Comparison of Walls 1-4 Depth-damage Curves - Saltwater

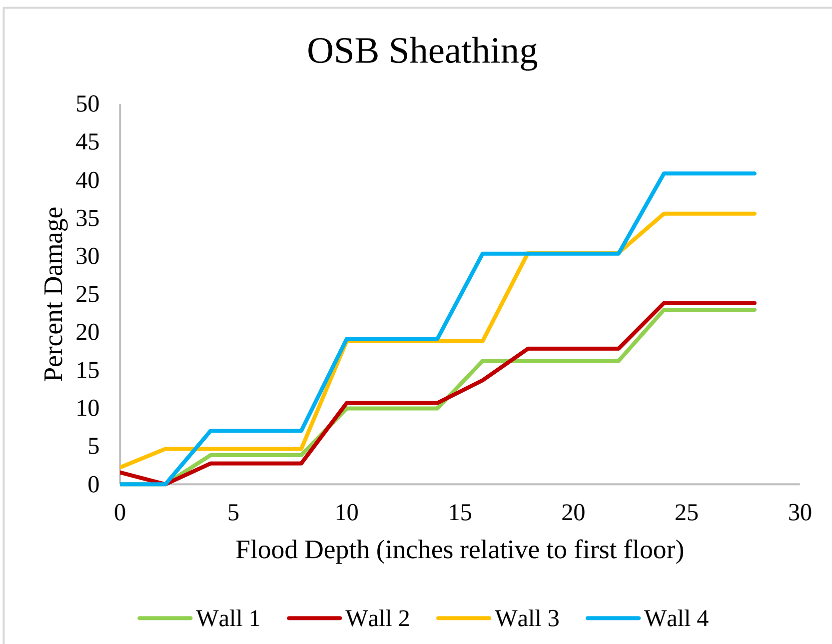

Figure B-60: Comparison of Walls 1-4 Depth-damage Curves - Saltwater

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