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Masonry Structure Vulnerability and Strengthening Needs for Extreme Storm Surge and Sea Level Rise

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Abstract

This research investigates the vulnerability and strengthening of masonry structures against storm surge and sea level rise. In hurricane-prone regions, many existing masonry structures were built decades ago and lack contemporary design measures. Recent hurricanes have highlighted the weak response of masonry to storm surge, revealing poor design details and reinforcement corrosion. Despite the increasing use of masonry as a preferable alternative to wood foundations in flood-prone areas, there is a lack of experimental data to assess the condition of these structures. This study, initiated recently at the University of Houston, aims to bridge this knowledge gap by providing insights and solutions for the masonry design community. The research involves fabricating 1:6-scale loadbearing masonry walls using various design schemes (ungrouted and partially grouted) and testing them under simulated storm surge conditions in the wave flume facility at the University of Houston. The project's goal is to develop an understanding of the vulnerability of masonry structures and study mitigation strategies, thereby enhancing masonry resistance in hurricane-prone regions. This research contributes to safer masonry design practices against extreme storm events.

Keywords

Flood risk, storm surge, wave flume, wave-structure interaction, structural masonry, hurricanes.

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INTRODUCTION

Evidence from past hurricanes has created the notion that structural masonry is vulnerable to extreme wave loads (Fig. 1). This is because of design practices in these regions that often produce poor connection details, include inadequate reinforcement, and inconsistent grouting. Even when reinforcement was used, field observations indicated severe corrosion and subsequent loss of capacity [1], leaving the masonry structures unrestrained against wave loading. Apart from on-site observations, there is limited quantifiable experimental or analytical data to assess the performance of masonry structures in hurricane-prone regions. Furthermore, there is no formal guidance to support their adaptation to the current state of knowledge of wave load demands. ASCE 7-22 Supplement 2 [2] contains the first major revision to Chapter 5 Flood Loads in 20 years, essentially revising the entire chapter, and ASCE 24-24 [3] is following suit. A major revision is the change from the 100-year to the 500-year flood as the design level event for Risk Category II structures. ASCE 7 Chapter 5 and ASCE 24 contain specific requirements for breakaway walls, many of which are dominated by the timber industry, designed to fail in an intentional manner under flood loading. Proposed changes in ASCE 24 would allow some dry floodproofing in Coastal A zones where wave action is expected to be significant.

Figure 1: Masonry wall failures during past storm surge events [4, 5].

Currently, the National Structure Inventory [6] database indicates that 17.94% of the low-rise structures in Galveston, TX include masonry materials (Fig. 2), underlining the need to develop strategies that can protect these structures from extreme storm events. This point was further emphasized by the 2024 Helene and Milton hurricanes that had devastating consequences to the coastal structures in West Florida, many of which are utilizing structural masonry members, including walls and columns.

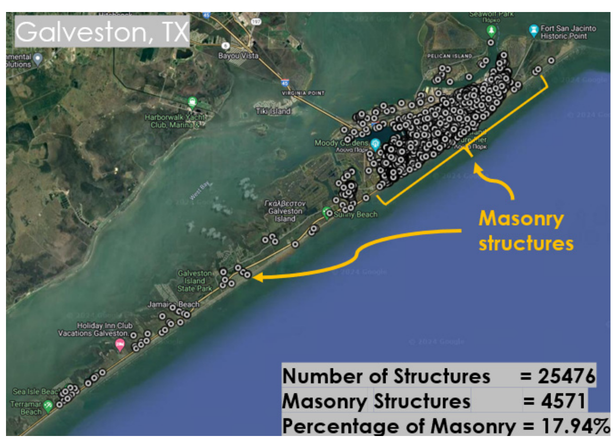


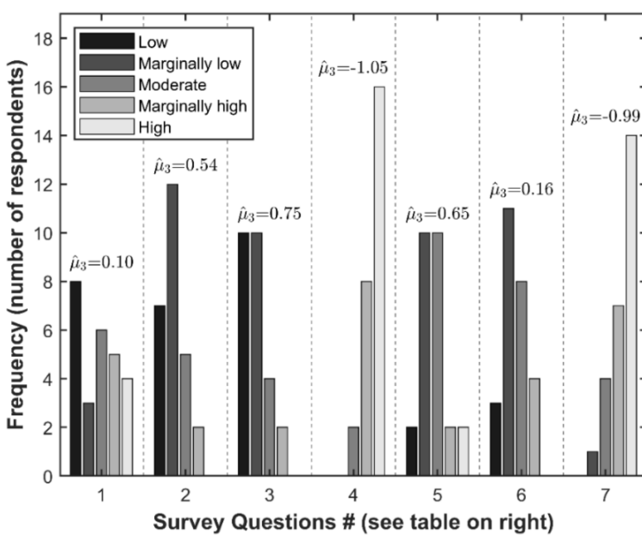
Figure 2: Masonry building statistics in the hurricane-prone region of Galveston, TX with the data being visualized with the google maps application [7].

The overall scope of this research program is to better understand the current state of the art about structural masonry design in hurricane-prone regions by seeking expert opinions and performing a series of experiments in small- and large-scale wave flume facilities. This paper presents an overview of the research program with some preliminary findings and future plans. Generated data from this project are expected to create a foundation basis to understand how structural masonry as nearshore construction responds to storm surge events.

EXPERT SURVEY

In the context of exploratory research, a preliminary survey was initiated at The Masonry Society (TMS) 2024 Annual Fall Meeting in Portland (ME) to assess the perspective of industry professionals and academic scholars on the flood resilience of masonry structures. The sectoral distribution of the survey sample (so far, n = 26) has been comprised of professionals in Consulting (34.6%), Academia (34.6%), Non-Profit Organizations (19.2%), and other relevant sectors (11.5%). Professional experience among respondents ranged from 0-52 years, skewing toward early-career professionals (mode: 4 years, 15.4%). The survey was implemented with a five-point Likert scale (1-5), where 1 indicated the lowest agreement/confidence and 5 represented the highest agreement/confidence. The third moment of the mean, ($\hat{\mu}_3$), was calculated to quantify response distribution skewness around the neutral value (3 - Moderate), providing insight about the directional bias in the participants' responses.

Preliminary analysis of the ongoing exploratory survey has so far revealed limited familiarity with the performance of masonry structures under extreme weather events, as depicted in Fig. 3. Specifically, for hurricanes, respondents reported significantly low familiarity with the resiliency of masonry structures in past hurricane events (Question 1), the availability of design and analysis resources against flood loads (Question 2), and the understanding of flood risk assessment during hurricanes (Question 3).



Question #	Question
1	Familiarity with the performance of masonry structures during past hurricane events?
2	Familiarity with available resources for the analysis and design of masonry structures for flood loads?
3	Current level of understanding regarding the flood risk of masonry structures in hurricane events?
4	Importance of flood load analysis for masonry structures located in hurricane-prone regions with the potential of high flood loads?
5	Confidence in the ability of current design practices to account for the effects of extreme storm surge and wave events (e.g., hurricanes) on masonry structures?
6	Adequacy of resources for the retrofit of existing masonry structures to resist flood loads?
7	Need for the masonry design community to provide flood load masonry design guidelines?

Figure 3: Survey responses for Likert-scale type questions. Skewness ($\hat{\mu}_3$) values indicate the distribution of responses, with negative values suggesting a tendency toward higher confidence or agreement and positive values indicating more skepticism or uncertainty.

All three responses were positively skewed with $\hat{\mu}_3$ = 0.10, 0.54, 0.75, respectively, which indicates a lack of consideration of the storm surge behavior of masonry structures. Despite the identified knowledge gaps, respondents strongly advocated for the consideration of fluid-structure interaction (FSI) analysis (Question 4) and the development of standardized design provisions for flood-resistant masonry structures (Question

7). The significant negative skewness in these responses, $\hat{\mu_3}$ = -1.05 and -0.99, respectively, reflects a strong consensus regarding the need of incorporating fluid-structure interaction analysis for hurricane-resistant masonry design. Finally, the analysis indicated the limited confidence that professionals have in two interconnected areas: the capability of current design practices to resist extreme hydrodynamic loads (Question 5) and the adequacy of present resources for flood proofing already existing masonry structures (Question 6, $\hat{\mu_3}$ = 0.16). The positive skewness, $\hat{\mu_3}$ = 0.65 and 0.16 respectively, reflects the perceived limitations of current design practices against extreme weather events.

Following the exploratory survey, the current pool of respondents proceeded with the evaluation and ranking of five identified methodological approaches for advancing flood-resistant masonry design. These were: (a) conventional quasi-static verification testing, (b) wave flume experimental verification testing, (c) development of design guidelines, (d) adaptation of existing design methods (e.g., seismic), and (e) creation of educational workshops on flood risk assessment in masonry structures and resource availability.

The results from the ranking survey indicated several patterns, as depicted in Fig. 4. The development of design guidelines received the highest priority (Rank 1), while both experimental verification approaches (wave flume experiments and conventional quasi-static testing) were ranked significantly lower, Rank 4 and Rank 3, respectively. Despite their lower ranking, these experimental methods are essential for validating theoretical models and informing future design guidelines. Their perceived lower priority may stem from the view that they represent foundational steps requiring further investment. The creation of educational workshops was also ranked in the middle (Rank 3), which corroborates the results from the exploratory survey, where most respondents reported moderate or below familiarity with available resources. Notably, the ranking distribution lacked consistency in the fifth position (Rank 5), as respondents frequently assigned equal ranks to multiple options, indicating the perceived identical value of certain approaches. This distribution of rankings indicates the recognition of the interdependent relationship between these proposed methodological approaches.

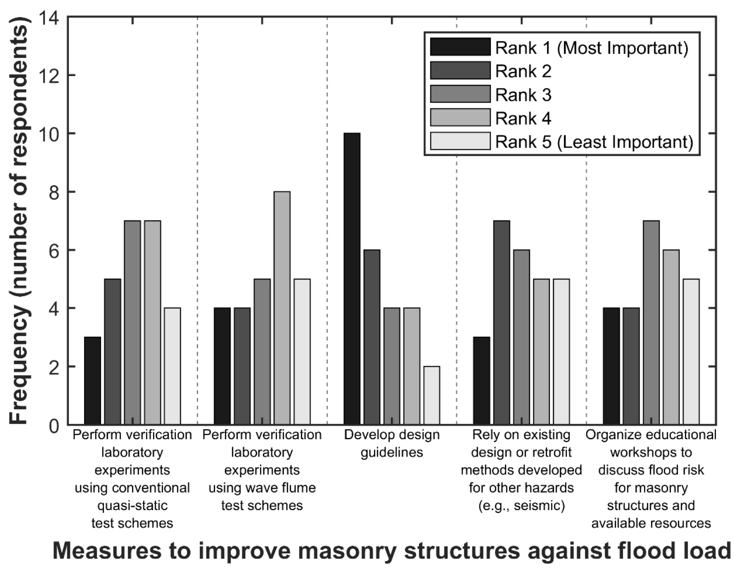


Figure 4: Survey responses to the ranking question regarding additional progress that is needed to improve the design or retrofit of masonry structures against flood loads.

Finally, the respondents had the option to address two concluding open-ended questions related to: (a) the adequacy of existing retrofit measures for flood-resistant design and (b) current and emerging needs in hurricane resilient masonry design.

The responses to the first open-ended question, regarding retrofit methodology adaptation for flood-resistant design, yielded two recurring observations. Firstly, it was emphasized that adapting the retrofit measures that exist in seismic design to flood loads would introduce unnecessarily high safety factors, raising concerns about cost-effectiveness. Secondly, it was noted that a technical consideration of the substantial out-of-plane forces is warranted, since these are introduced during flood loading but are not present in seismic design. Lastly, the responses addressing future requirements in flood-resistant masonry design highlighted three key areas for development. Significant emphasis was put in developing specialized design provisions that focus on flood loads, wave impacts, and waterproofing, rather than adapting solutions from seismic design. In addition, many highlighted the lack of educational masonry design courses and professional training and identified the necessity for additional research needed to characterize the hydrodynamic responses of masonry structures, specifically investigating the inherent structural strengths of arching action and redundancy.

Despite experimental verification approaches receiving lower priority rankings (Rank 3 and 4) compared to design guidelines (Rank 1), experimental methods were nonetheless recognized as fundamental for validating theoretical models and informing future design provisions regarding the substantial out-of-plane forces introduced during flood loading. To address this knowledge gap, an experimental program incorporating 10 masonry walls under wave action is being prepared. The wall specimens include various configurations: Plain and C-shaped masonry walls, grouted and ungrouted walls, and walls with vertical reinforcement or bond beams. These laboratory experiments are performed at 1:6 scale to better understand the hydrodynamic response of masonry structures. Results will support validation of multi-physics models and the development of a large-scale wave flume testing program.

EXPERIMENTAL RESEARCH PLAN

An experimental program focusing on 1:6-scale tests of out-of-plane masonry walls against wave action has been initiated at the University of Houston. The experimental program is under preparation and will be performed using the in-house wave flume facility.

Test Matrix

The experiments employ prefabricated 1:6-scale full-size and half-size concrete masonry units (CMUs), with sizes of 66 mm x 33 mm x 33 mm (2.6 in. x 1.3 in. x 1.3 in.) and 33 mm x 33 mm x 33 mm (1.3 in. x 1.3 in. x 1.3 in.), respectively. Both full-size and half-size CMUs are made with a mix of lithium carbonate, portland cement, quartz, and sand. The prefabricated mixes of "Mini Cinder Block Cement Mix" and "Mini Cinder Block Mortar" is used for grout and mortar, respectively.

Compressive tests have been performed for both full-size and half-size CMUs using the load protocol outlined in Section 7 of ASTM C140/C140M – 24a [8] using a FORNEY F-25F compression machine at the University of Houston. Pliable lead sheets were used as the interface between the loading plates and the CMU surfaces to ensure uniform load distribution. The average compressive strength of the half-size and full-size was reported to be 18.6 MPa (2.7 ksi) and 27.2 MPa (3.9 ksi), respectively. Examples of the CMU specimen failures are shown in Fig. 5.

(a) (b)

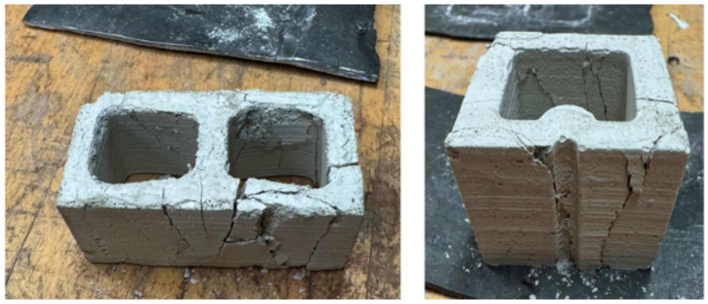


Figure 5: Specimens after testing: (a) full-size CMU and (b) half-size CMU.

Ten wall configurations have been designed for the wave flume tests, as shown in Table 1. All walls are 330 mm high and 297 mm wide (13 in. x 11.7 in), consisting of 10 courses of CMUs. Plain walls are comprised of 40 full-size and 10 half-size CMUs and C-shape walls are comprised of 80 full-size CMUs and 10 half-size CMUs. A running bond pattern is used across all wall specimens per standard masonry construction practices in the United States.

The test variables in the wall configurations are: (a) presence of vertical reinforcement, (b) ungrouted versus partially grouted walls, (c) use of bond beams, and (d) wall shape (plain and C-shape walls). These design variables are selected based on their influence on structural integrity, out-of-plane resistance, and common design practices of masonry. Some walls are designed with weakened bed joints to simulate erosion effects in mortar joints, which is common in coastal regions.

Table 1: Test Matrix of Wall Configurations

Wall ID	Wall Configuration	Grouting	Reinforcement
Wall-1	Plain Wall	Ungrouted	None
Wall-2	Plain Wall with Weakened Bed Joints	Ungrouted	None
Wall-3	Plain Wall with Weakened Bed Joints	Partial	None
Wall-4	Plain Wall with Weakened Bed Joints	Partial	Vertical Reinforcement
Wall-5	Plain Wall	Partial	Vertical Reinforcement
Wall-6	C-Shape Wall	Ungrouted	None
Wall-7	C-Shape Wall with Weakened Bed Joints	Ungrouted	None
Wall-8	C-Shape Wall with Weakened Bed Joints	Partial	None
Wall-9	C-Shape Wall with Weakened Bed Joints	Partial	Vertical Reinforcement
Wall-10	Plain Wall with Bond Beams	Partial	None

Vertical reinforcement in the walls is simulated with slender TIG welding rods (VULCAN 2.4 mm AWS ER5356 TIG Welding Rods). The reinforcement, when present in the walls, is placed in the center and end cells, with a horizontal spacing of 132 mm (5.20 inches) center-to-center (C/C). Figure 6 provides an example of two wall geometries, a plain wall that is partially grouted and reinforced (Wall 5) and a partially grouted C-shape wall with no reinforcement and weakened bed joints (Wall 8).

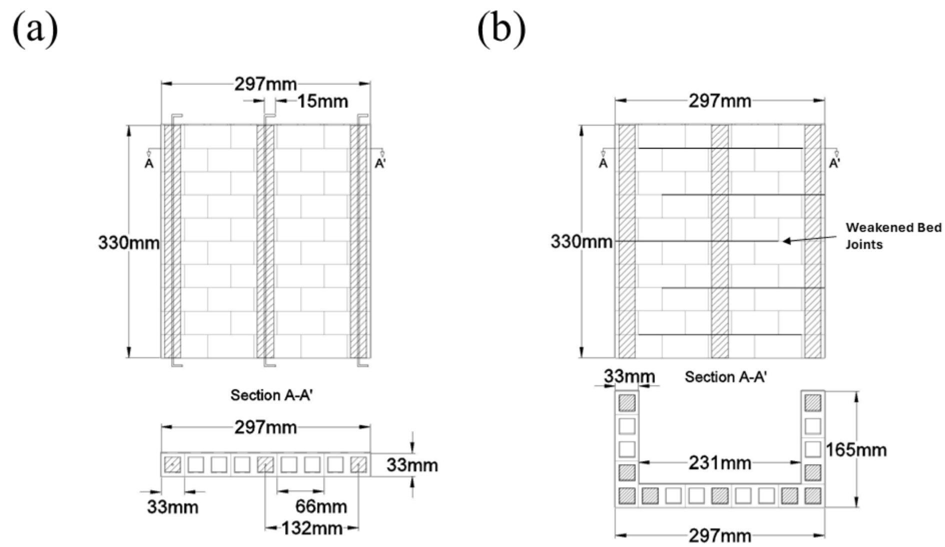


Figure 6: (a) Schematic of plain Wall-5 and (b) schematic of C-shape Wall-8.

Experimental Setup

The wave flume at the University of Houston was recently established in collaboration with HR Wallingford. It consists of a steel-framed water tank with a usable length of 1,220 cm (40 ft), a usable width of 762 mm (30 inches) and a usable depth of 813 mm (32 inches). It has a beach slope with an inclination of 1:8. The beach slope is specially fabricated with a foam-based material to minimize wave reflection effects. A water re-circulation system is included in the wave flume to ensure preservation of the undisturbed water level during a sequence of tests. The maximum water depth in the flume, to ensure stable testing conditions and avoid water spilling, is 518.2 mm (20.4 inches). An overview of the wave flume is presented in Fig. 7.

Waves are generated with a piston-type wavemaker of HR Wallingford design. The wavemaker has a maximum paddle stroke of 600 mm (23.6 inches). A system of wave probes is mounted on the wavemaker to track the undisturbed water level in the flume. An active absorption system is embedded in the wave generation system to minimize wave reflection. Wave generation is programmed with the HR Merlin software v2.50. This is a wave synthesizer program developed by HR Wallingford what can generate regular (sinusoidal), irregular, and solitary waves based on predefined functions and spectral forms. The irregular waves that can be produced by the software conform to several standard spectral shapes.

After fabrication of the CMU walls, each wall is attached to 3D-printed formworks designed for casting the concrete foundation and floor beams. The walls and beams are cast monolithically to ensure proper bonding between the components to provide adequate reinforcement development lengths. The 3D-printed formwork is designed to have cylindrical voids, which are utilized for connecting the wall-beam assembly to the test frame using threaded rods. The wall assembly is connected to a custom test frame fabricated from 12.7 mm (0.5 in.) thick transparent plexiglass to create one-dimensional wave loading conditions. Additionally, the test frame serves as the mounting point for the instrumentation to record the out-of-plane wall deflections and forces. An overview of the test setup is shown in Figs. 8, 9.

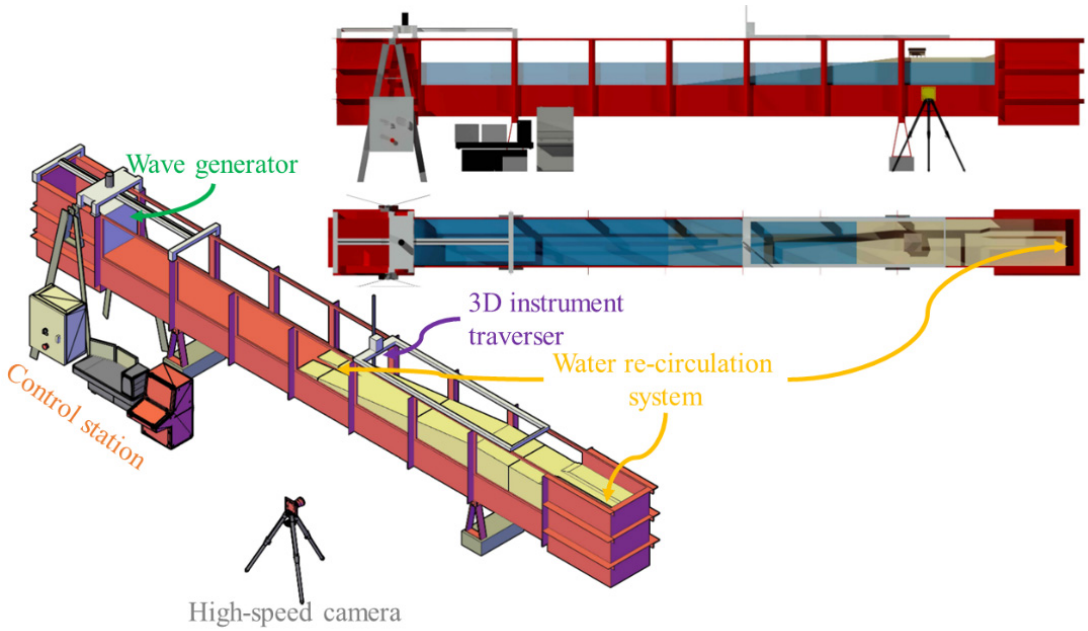


Figure 7: Wave flume facility at the University of Houston.

Wall Instrumentation

The structural response is monitored using two miniature load cells (CLS-5KNB) with a 5 kN capacity, measuring the out-of-plane wave impingement force transferred to the foundation and floor beam, respectively. Additionally, a DC linear variable differential transformer, LVDT (T-750-D-500), with a ±12.7 mm (±0.5 in.) measuring range is installed to record the out-of-plane deflections at the wall mid-height. The hydrodynamic pressure-impulse profile is captured using an array of four miniature pressure transducers with a capacity of 3 MPa (PDA-3MPB), installed vertically along the wall centerline. The transducers are distributed with higher concentration at lower elevations to better capture the wave run-up. The coordinates of all wall instrumentation with respect to the wall centerline are provided in Table 2.

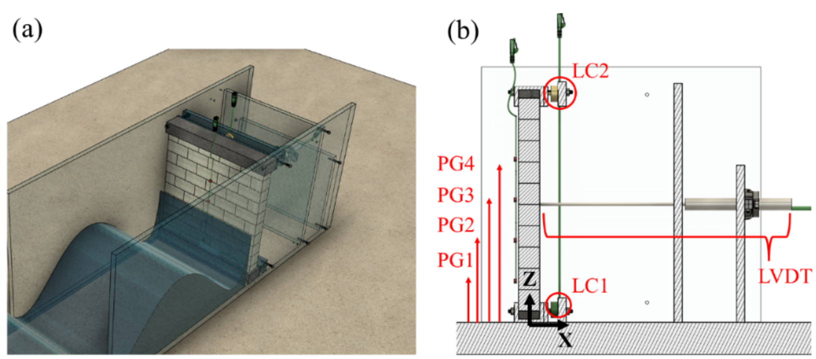


Figure 8: (a) Orthographic view of the test setup of single masonry walls. (b) Masonry wall instrumentation plan with two load cells (LC1 and LC2), one linear variable differential transformer (LVDT), and five pressure gages (PG1-PG4).

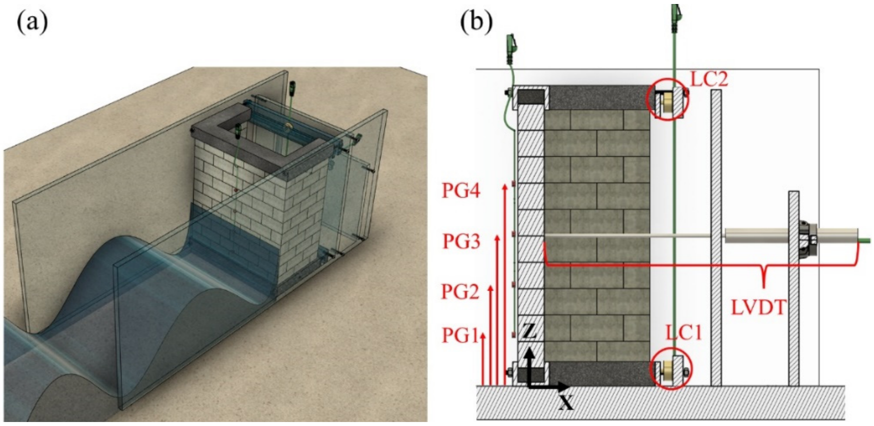


Figure 9: (a) Orthographic view of the test setup for C - shaped masonry walls. (b) C - shaped masonry wall instrumentation plan with two load cells (LC1 and LC2), one linear variable differential transformer (LVDT), and five pressure gages (PG1-PG4).

Regular sinusoidal and solitary waves are generated to evaluate each specimen under wave conditions derived from historical storm surge events in the Gulf Coast. These conditions are selected based on spectral wave data collected at various stations incorporated by the United States Army Corps of Engineers Wave Information Study (WIS) project. The spectral wave data is classified in Fig. 10 with respect to wave theory functions and wave steepness. Testing proceeds with progressively intensifying wave conditions until specimen failure.

Table 2: Instrumentation coordinates with respect to each wall centerline.

	Instrument	***X***	***Z***
Single Masonry Walls	LC1	140 mm (5.50 in.)	19 mm (0.75 in.)
	LC2	140 mm (5.50 in.)	355 mm (14.00 in.)
	PG1	-17 mm (-0.65 in.)	63.5 mm (2.50 in.)
	PG2	-17 mm (-0.65 in.)	127 mm (5.00 in.)
	PG3	-17 mm (-0.65 in.)	190 mm (7.50 in.)
	PG4	-17 mm (-0.65 in.)	254 mm (10.00 in.)
	LVDT (Core Tip)	17 mm (0.65 in.)	155 mm (6.10 in.)
	LVDT (Housing)	241 mm (9.50 in.)	155 mm (6.10 in.)
C- Shaped Masonry Walls	LC1	161 mm (6.35 in.)	19 mm (0.75 in.)
	LC2	161 mm (6.35 in.)	355 mm (14.00 in.)
	PG1	-17 mm (-0.65 in.)	63.5 mm (2.50 in.)
	PG2	-17 mm (-0.65 in.)	127 mm (5.00 in)
	PG3	-17 mm (-0.65 in.)	190 mm (7.50 in.)
	PG4	-17 mm (-0.65 in.)	254 mm (10.00 in.)
	LVDT (Core Tip)	17 mm (0.65 in.)	155 mm (6.10 in.)
	LVDT (Housing)	241 mm (9.50 in.)	155 mm (6.10 in.)

Small-scale testing of wave-structure interaction phenomena is characterized by an inherent scaling incompatibility between the hydrodynamic and structural forces. Froude scaling (equation 1) is used in reduced-scale wave flume tests to preserve the ratio of inertial to gravitational forces. Froude similitude, F_r, is defined as:

$$F_r = \frac{u}{\sqrt{g \cdot L}} \tag{1}$$

where u is the wave celerity; L is the characteristic length; and g is the gravitational acceleration. However, Froude scaling may distort the structural scale. This incompatibility means that when wave dynamics are correctly scaled using Froude similitude and identical materials are employed in both prototype and model, the structural stiffness-to-mass ratio may not be accurately scaled. However, the results of this small-scale program provide a basic understanding of wave-masonry interaction phenomena that will guide the development of a large-scale experimental program to capture structural responses under waves more realistically.

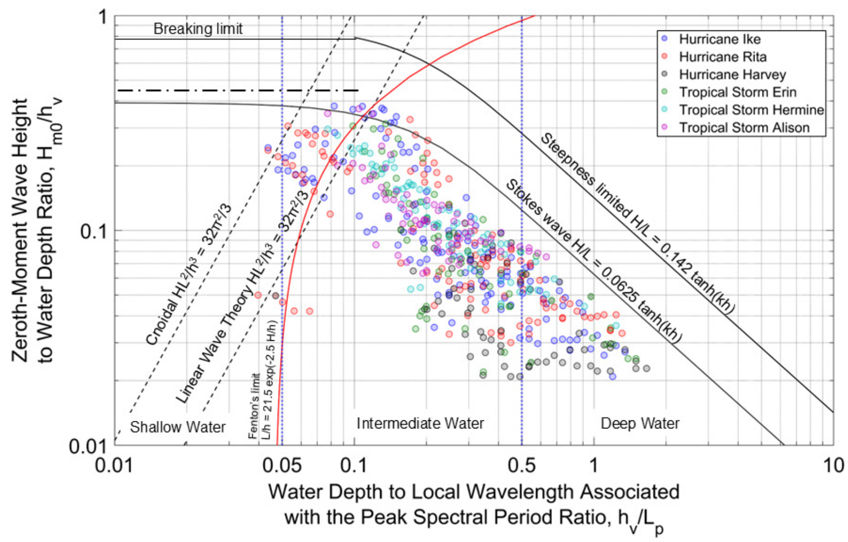


Figure 10: Spectral wave parameters recorded at WIS stations in the Gulf Coast during storm surge events.

DISCUSSION

Hurricanes have been the costliest natural hazards in the recent history of the United States, causing significant damage and loss of life. Due to only four recent hurricane events—Sandy (2012), Maria (2017), Irma (2017), and Harvey (2017)—the economic losses amounted to about $330 billion. These losses were attributed largely to the poor performance of nearshore structures and buildings under high wind, storm surge, and wave loads, including those with structural masonry members. Despite this poor performance, little has been done to understand and improve the performance of structural masonry under these extreme events. Within the path toward sustainability and resiliency, structural masonry can play a key role by providing a cost- and energy-efficient solution that can effectively resist future extreme weather events. Nevertheless, the superior performance of structural masonry against storm surge events has not been quantified, or demonstrated by any means, through a rigorous research study.

Preliminary results from this program show that the masonry community underlines the need for design guidelines that will educate and inform policymakers and practitioners on how to appropriately design and construct masonry structures in hurricane-prone areas. Experimental data from this program are expected to provide an improved understanding of how masonry walls respond to storm surge loads.

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