Paper:

Wave Impact Study on a Residential Building

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[Received July 29, 2009; accepted November 4, 2009]

Recent natural disasters around the world including both tsunamis and hurricanes, have highlighted the inability of wood buildings to withstand wave and surge loading during these extreme events. Little is known about the interaction between coastal residential light-frame wood buildings and wave and surge loading because often little is left of the buildings. This leaves minimal opportunity for forensic investigations. This paper summarizes the results of a study whose objective was to begin to better understand the interaction between North American style residential structures and wave loading. To do this, one-sixth scale residential building models typical of North American coastal construction, were subjected to tsunami wave bores generated from waves of heights varying from 10 cm to 60 cm. The lateral force produced by the wave bores were, as expected, found to vary nonlinearly with parent wave height.

Keywords: tsunami, hurricane, wave, bore, residential building, light-frame wood

1. Introduction

On December 26, 2004 the second largest earthquake ever was recorded on a seismograph off the west coast of Sumatra, Indonesia. An M9.1 [1] earthquake was recorded for an estimated 10 minutes, making it the longest earthquake ever recorded. This earthquake triggered what became known as the Great Indian Ocean Tsunami. Coming ashore in Indonesia, this tsunami reached an estimated 10-30 meters [1] and affected regions as far away as Somalia. The United Nations estimated that 229,866 people were lost (missing or deceased) with over one million people displaced making the Great Indian Ocean Tsunami the deadliest tsunami in all recorded history.

The 2005 Hurricane Katrina ranks as one of the deadliest water-based natural disasters in United States history. Formed over the Atlantic, it made landfall in the U.S. state of Louisiana, as a Category 3 hurricane on August 29th.

Fig. 1. The foundations of houses in waveland, mississippi, USA following Hurricane Katrina in 2005.

According to the final estimates, 1,836 people lost their lives in the states of Mississippi, Louisiana, Alabama, Florida, Georgia, Kentucky, and Ohio. **Fig. 1** shows what remained of waterfront houses in Waveland, Mississippi immediately following the hurricane. Both hurricanes and earthquakes, while from very different sources, result in waves that can interact with residential coastal structures.

In the United States, the Cascadia Subduction Zone (CSZ) fault runs from Northern California to British Columbia and is less than 100 miles offshore in most places (**Fig. 2**). A 9.0 magnitude earthquake along this fault will trigger a massive tsunami, similar to the one that occurred in the Indian Ocean in 2004. The wave will be over 10 m (33 ft) high and will hit the Pacific Northwest coast within approximately 30 minutes [2]. According to the USGS, the probability of having the CSZ event in the next 50 years is 14% [3]. The US has invested heavily in a tsunami warning system with a worldwide network of buoys, but unfortunately this system does little to help the Northwest United States, i.e. Washington and Oregon, against a near field tsunami [4], putting a tremendous population at risk. The city of Seaside, Oregon, for example, is a coastal town with a base population of 5,000 and as

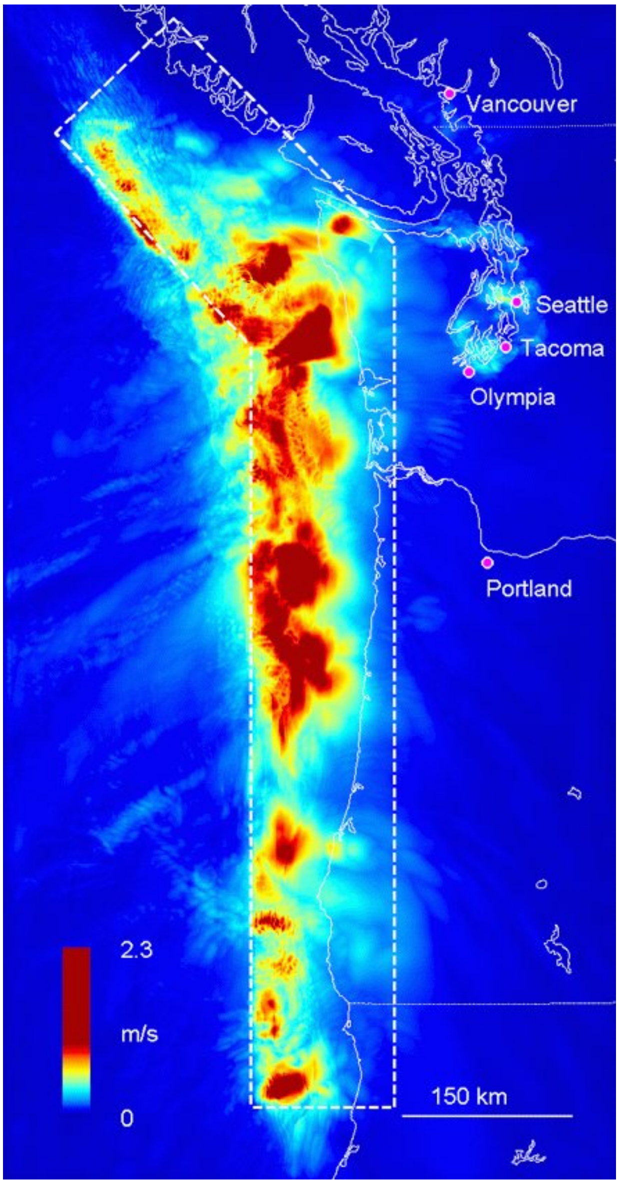

Fig. 2. Cascadia subduction zone threat to the U.S.

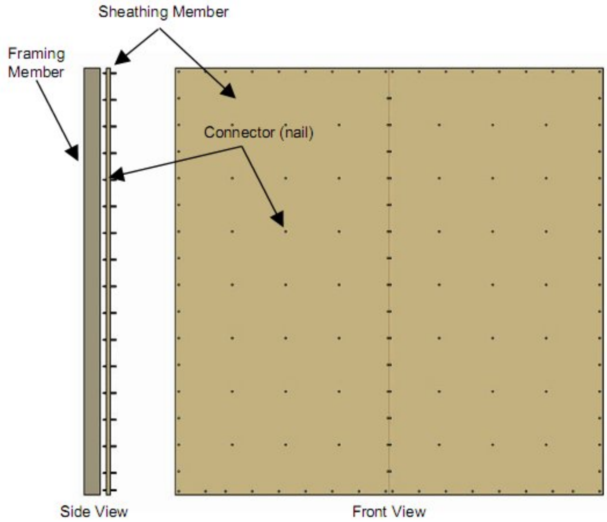

Fig. 3. Components making up a wood shear wall in a light-frame wood building.

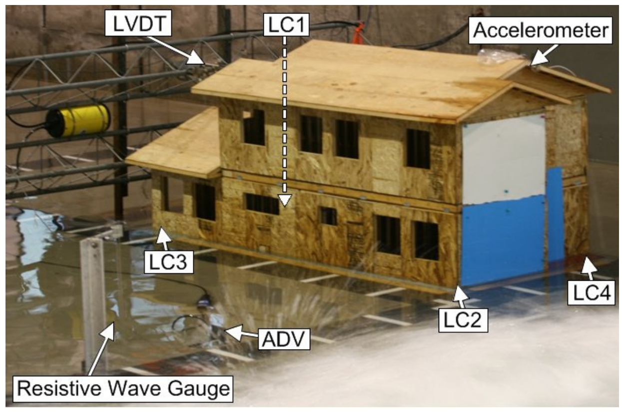

Fig. 4. Fully assembled structure with instrumentation in the tsunami wave basin.

many as 10,000 tourists in the summer. It takes about 30 minutes to evacuate people on the waterfront to an area outside the inundation zone, approximately the same time that it will take for the near field tsunami to strike. Thus, understanding the interaction between residential buildings and waves is critical to the application of engineering principles to better protect these at-risk communities and help plan evacuation strategies.

The vast majority of the building stock in North America is light-frame wood construction which is typically made up of dimension lumber (e.g., 2 × 4's) combined with sheathing materials such as oriented strand board (OSB) or plywood. The lateral resistance of the building is primarily due to the sheathing-to-framing nails in the shear walls. **Fig. 3** shows a simple diagram of a wood shear wall that would typically be in a light-frame wood building. The outside of the building typically consists of some exterior finish material which is not included in the design strength but provides some strength, stiffness, and continuity. The interaction of a one-sixth scale light-frame wood residential structure with tsunami bores from waves generated at increasing wave heights at Oregon State University's Hillsdale wave Laboratory was pursued in this study. The building was designed to exhibit compliant behavior at approximately one-sixth scale when subjected to wave loading.

2. Brief Building Description

The test structure was constructed to simulate light-frame wood buildings similar to that found in coastal regions of the United States. A structurally compliant 1/6 scale model of a two-story residential structure was built. **Fig. 4** shows the assembled one-sixth scale building prior to testing. The walls were assembled on a 13 mm × 1100 mm × 2400 mm steel plate. The plate was used as slab-on-grade foundation or crawl space type foundation

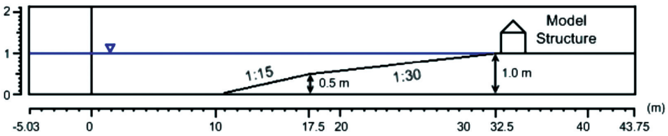

Fig. 5. Elevation view of the tsunami wave basin.

depending upon whether metal flashing was used around it or not. Walls were attached to the steel plate using 3 mm × 25 mm stainless steel anchor bolts through the bottom plate of the walls, at 125 mm on-center based on the prescriptive code [5]. The final dimensions of the structure are 2400 mm long × 1100 mm wide × 1200 mm high (aspect ratio ∼ 2 : 1). The model has several structural irregularities, including a reentrant corner near the front door and a second story floor diaphragm that doesn't extend over the garage. Complete details can be found in Wilson [6] and Garcia [7].

3. Description of Wave Tests

Testing was performed at the Oregon State University Tsunami Wave Basin (TWB) and involved impacting the wood structure with a series of waves and recording the force in four load cells (LC1, LC2, LC3, LC4), deflection (Δ_{wave}), bore height, and wave velocity, as shown in **Fig. 4**. The TWB bathymetry is shown in **Fig. 5**. In this study, the wave maker generated 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm solitary waves (a shallow water *wave* that consists of a single displacement of water) in depths of both 1 m and 1.1 m in successive tests. The structure was placed on a flat testing area with its front edge 10 cm back from the water's edge. This was done so the waves would have broken by the time they reach the structure yet would still have much of their initial energy. The structure was tested with its long face towards the oncoming waves, hereafter referred to as the 0° orientation, as well as rotated 90° with its short face toward the oncoming waves, hereafter referred to as the 90° orientation.

The structure had openings at window and door locations, which were covered in some trials by rigid plastic to simulate boarded windows. There was approximately a 4 cm gap beneath the steel plate which was needed because of the placement of the load cells, which in some trials was covered by a thin gauge sheet metal flashing to prevent water intrusion beneath the plate. This modeled the presence of an open crawlspace versus a slab/stem wall foundation. In several trials, the structure was raised an additional 5 cm using rigid aluminum risers. This was to simulate the effects of a slightly elevated structure.

Force was measured using four uniaxial load cells (LC1 – LC4) placed in each corner beneath the structure, effectively measuring the tension and compression forces generated by the waves impacting the structure. Deflection (Δ_{wave}) was measured at the second story roofline using a linear variable differential transformer (LVDT). Wave height was measured using a resistive wave gauge (surface piercing gauge used to measure wave height), and wave velocity was measured using an acoustic doppler velocimeter (ADV). A total of 142 trials were conducted. Specifically, there were 43 trials in the 0° orientation and 99 trials in the 90° orientation, as shown in **Table 1**. The following abbreviations were used to indicate the specific testing configuration: 90 = 90° Orientation, 0 = 0° Orientation, 1.0 = 1.0 m water depth, 1.1 = 1.1 m water depth, WO = Windows open, WC = Windows closed, F = Flashed; NF = Not Flashed, E = Elevated structure (baseplate ∼10 cm above concrete floor), and NE = Non-Elevated Structure (base plate 4 cm above concrete floor). Example: 90-1.1-WC-F-NE indicates a test conducted in the 90° orientation, with the water level at 1.1 m, window and door coverings installed, base plate flashed to prevent water intrusion, and the structure fixed to the foundation in a non-elevated position. The flooded condition is indicated by a 1.1 m water depth (1.1) and a non-elevated structure (NE).

4. Interpretation of the Test Results

During the wave lab trials, several trends were expected from the data during the different loading conditions. It was expected that there would be overturning moment generated by the wave loading and that this would cause the front two load cells to be in tension and the rear two load cells to be in compression at approximately the same, but opposite forces. To some extent, it was expected to see uplift from water intrusion beneath the steel plate when metal flashing was not installed below the base plate. It was also expected that the force per unit width would be the same for the 0° and 90° orientations.

A summary of wave forces on the structure is shown in **Table 2**. **Fig. 6** shows load and deflection plots for all eight trials for the 60 cm high wave impact. Recall from above that the 60 cm wave was the largest generated for this series of experiments, i.e., 10 cm to 60 cm. The plots each show four load time histories; one at each of the four corners of the building (see **Fig. 4**) and the deflection which was measured at the top of the building (see **Fig. 4**). Negative load cell readings indicate compression and positive ones indicate tension.

For three trials (trials 2, 4, and 5), there is only uplift force because water was allowed to go underneath the building no flashing was installed. This simulated raised structures along the coast line where hurricane storm surge or tsunami wave loading may cause the structure to be uplifted from its foundation if sufficient anchorage is not provided. If the buildings are flooded when surge waves hit the building these uplift forces can be even higher (trial 2 versus trial 4 and 5). If the windows are open or they have been blown out, then water enters the building and the uplift force is reduced due to the weight of the water (trial 4 versus trial 5). However, it should be noted that this type of force reduction is clearly more relevant for hurricane wave and surge than to tsunami

Table 1. Test matrix for wave lab trials.

Wave Height (cm)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8
10	0	2	2	0	2	2	0	2
20	0	4	2	7	7	2	4	4
30	0	3	2	2	0	2	0	2
40	8	4	2	8	9	4	3	4
50	0	1	2	2	2	2	0	2
60	7	4	2	3	10	3	5	2

Trial 1: 90-1.0-WC-F-NE; Trial 2: 90-1.0-WO-NF-NE; Trial 3: 90-1.1-WC-F-NE; Trial 4: 90-1.1-WO-NF-E; Trial 5: 90-1.1-WC-NF-E; Trial 6: 0-1.0-WC-F-NE; Trial 7: 0-1.0-WO-F-NE; Trial 8: 0-1.1-WC-F-NE

Table 2. Summary of wave forces.

Trial Name	Wave Ht. (cm)	# of Trials	LC2+LC4 (N)	LC1+LC3 (N)	Comment
90-1.0-WC-F-NE	40	8	91	-110	OM
(Trial 1)	60	7	288	-198	OM
90-1.0-WO-NF-NE	10	2	146	148	NUF
(Trial 2)	20	4	403	346	NUF
	30	3	538	441	NUF
	40	4	660	587	NUF
	50	1	686	618	NUF
	60	4	710	432	NUF
90-1.1-WC-F-NE	10	2	663	-259	OM
(Trial 3)	20	2	529	-97	OM
	30	2	470	-124	OM
	40	2	636	-221	OM
	50	2	803	-416	OM
	60	2	899	-455	OM
90-1.1-WO-NF-E	20	7	1293	1138	NUF
(Trial 4)	30	2	1874	1423	NUF
	40	8	1704	1560	NUF
	50	2	1758	1396	NUF
	60	3	2046	1462	NUF
90-1.1-WC-NF-E	10	2	744	613	NUF
(Trial 5)	20	7	1653	1338	NUF
	40	9	2226	1661	NUF
	50	2	2503	1966	NUF
	60	10	2739	2138	NUF
			LC2+LC3	**LC1+LC2**	
0-1.0-WC-F-NE	10	2	8	-74	OM
(Trial 6)	20	2	70	-197	OM
	30	2	206	-368	OM
	40	4	344	-629	OM
	50	2	667	-945	OM
	60	3	972	-1219	OM
0-1.0-WO-F-NE	20	4	45	-40	OM
(Trial 7)	40	3	258	-186	OM
	60	5	779	-349	OM
0-1.1-WC-F-NE	10	2	1764	-676	OM
(Trial 8)	20	4	782	-474	OM
	30	2	1325	-806	OM
	40	4	1961	-1307	OM
	50	2	2239	-1564	OM
	60	2	2672	-1773	OM

surge. All other trials had overturning moment (OM), as expected.

Following wave testing, a series of pushover tests were conducted on a nominally identical specimen at the OSU Wood Science and Engineering Structures Laboratory under dry conditions. Tests were conducted on the structure in both the 0° and 90° orientations. Loading was a distributed load applied at a variety of heights to determine the relationships between input loading (P_P), deflection (Δ_P) and the height of the equivalent applied load (H_P). Details of the loading can be found in Wilson [6]. The results of the push over tests were correlated with the equiv-

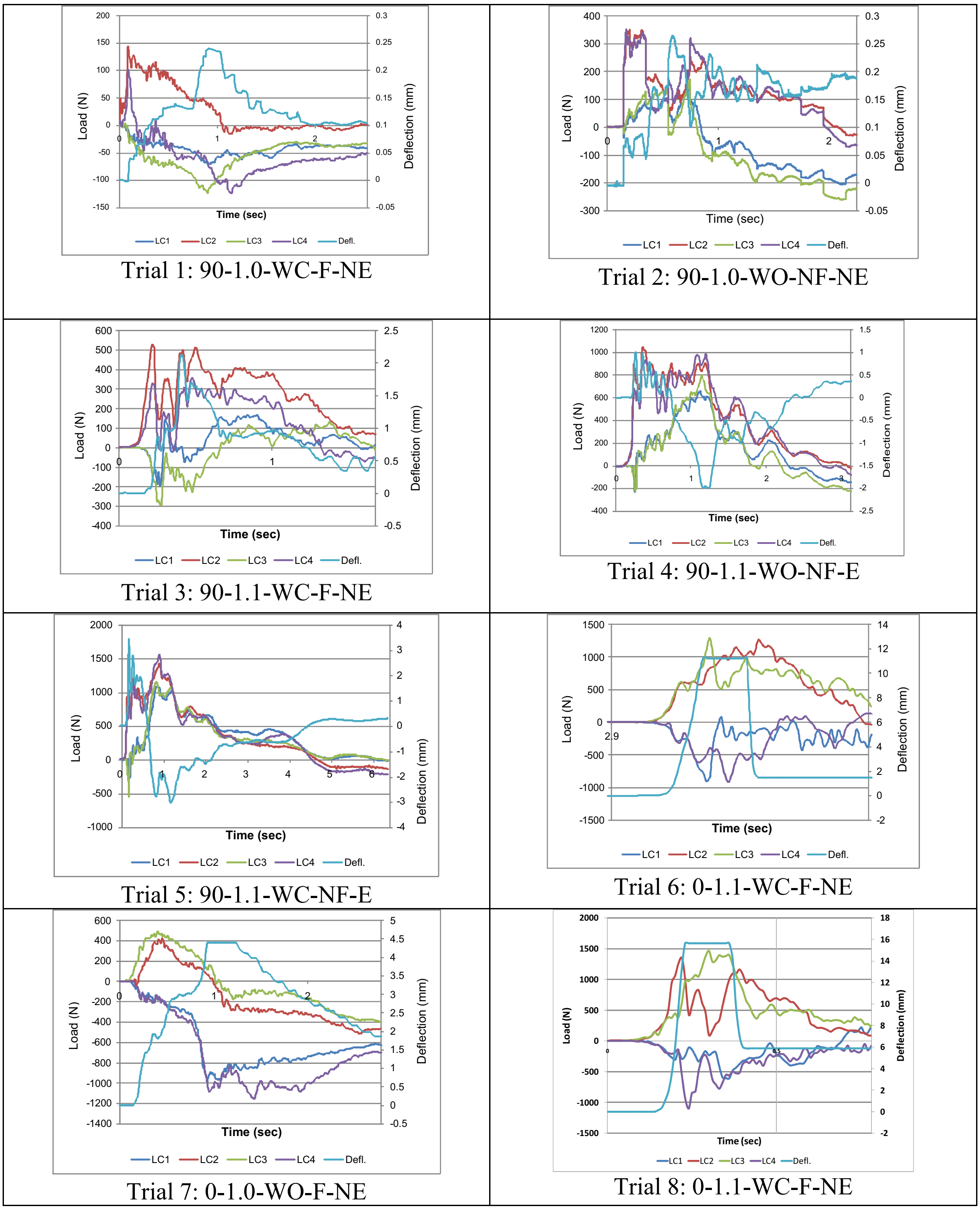

Fig. 6. Load time plots for 60 cm wave for trials.

alent structural displacements measured in the wave tank during testing to help in the interpretation of the wave data. Each test was conducted up to an average maximum load of 1400 N for the 0° orientation and 2200 N for the 90° orientation. These loads were different because the amount of shear wall resisting the lateral force was different for the two directions. Thus, this load was determined based on test observation while loading the structure, keeping the deflection within the linear range. The details of the push over tests are given in Wilson [6].

The exponential Eqs. (1) and (2) shown below provides the relationship between P_P and Δ_P for any given height, H_P for the 0° and 90° orientation, respectively.

$$P_P = \Delta_P \cdot 746 \cdot exp^{-0.03648 \cdot H_P} \quad . \; . \; . \; . \quad (1)$$

$$P_P = \Delta_P \cdot 4036 \cdot exp^{-0.04677 \cdot H_P} \quad . \; . \; . \; . \quad (2)$$

where, P_P is the input load, Δ_P is the combined load cell output, and H_P is the height of the applied load.

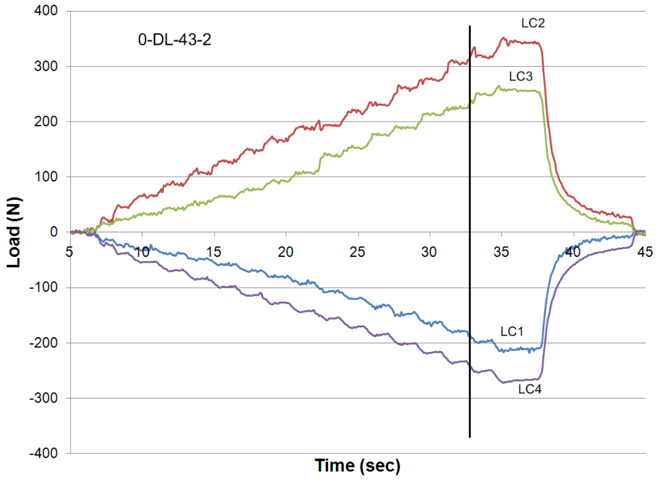

Fig. 7. Point in time when combined load cells are at the correspondingly maximum value in the push over trial.

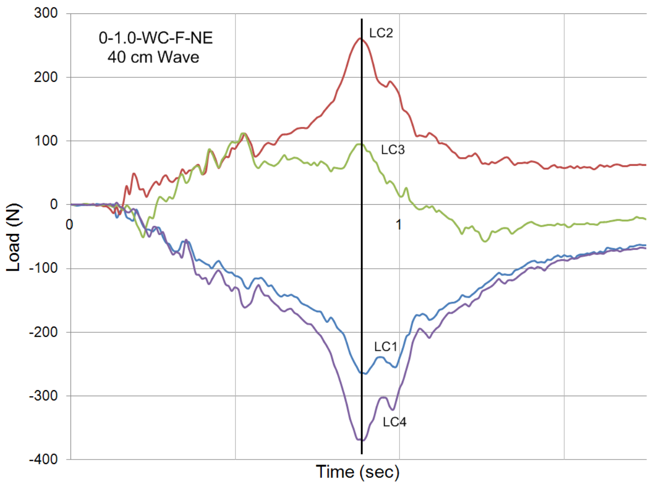

Fig. 8. Point in time when combined load cells are at a maximum value in wave lab trial.

5. Relating Pushover Tests to the Wave Lab Tests

As wave lab testing is complicated and expensive it would be valuable to be able to apply equivalent wave type forces under dry land testing conditions. This could be used as the first phase in structural testing prior to moving into the wave lab for testing. Of course, this type of simulation testing would not exactly replicate the myriad of forces and conditions developed during wave loading, but it may be able to mimic the reactions developed during surge loading. To this extent the combined load cell values from the wave lab trials were matched with similar combined load cell values for the push over tests to determine if the reactions matched, as depicted in **Figs. 7** and **8**.

To compare the load cell values (reactions) between the wave lab trials and the push over tests averaged load cell contributions were compiled, as shown in **Table 3**. There were four wave lab trials, each aligned in the 0-1.0-WC-F-NE orientation with a 40 cm wave height. There were 20 push over test trials; the structure was also aligned in the 0° orientation and loading was applied at a height of 43 cm.

Table 3. Averaged load cell values from wave lab and pushover trials.

	LC1(N)	LC2(N)	LC3(N)	LC4(N)
Push Over Trials	-205	303	216	-250
Wave Lab Trials	-286	214	130	-343
% Difference	39.8%	29.4%	39.7%	37.3%

As can be seen in **Table 3** there are differences between individual load cells, but the overall trends are the same. As the pushover tests applied controlled, distributed loading, it would follow that the wave loading had more complexity, which is not easily replicated. It is well known that there are multiple aspects to wave loading, and it is likely that the effects of hydrostatic and drag loads added additional variability to individual load cells that doesn't fit with the distributed loading assumed by the pushover tests. It is also reasonable to assume that differences between the nominally identical structural models used for wave lab trials and pushover trials may account for some portion of these differences.

Water as a natural force is no less complex than wind; both are fluids that apply force to structures as pressures. From the series of different configurations tested in this study and the varied results from each, it is clear that care must be taken to not over simplify the design of structures in coastal regions. Coastal structures, especially residential structures, show a great deal of architectural variety; if only one parameter is examined (e.g., the width of the structure) it is unlikely that good engineering design will follow. As discussed earlier, there are 60 pages detailing wind loading in ASCE 07-05 [8] and only 2 pages on wave loading, thus there is clearly a need to further detail the complexity of wave loading for the basic design of residential structures in coastal areas. More information about the study can be found in van de Lindt et al 2009 [9] and Wilson et al 2009 [10].

6. Summary and Conclusions

In this study a series of tests were performed to examine the behavior of a 1/6 scale model of a residential building subjected to wave loading. The building was tested in two different configurations to examine the effect of common design features and their effect on measured forces. Pushover tests were also performed to examine the ability to reproduce the forces measured in the wave laboratory. It can be concluded that it is possible to reproduce uplift forces in a dry structural laboratory, and this may eventually help with the application of equivalent loading to design. Such designs will be required to be targeted designs in which architectural and structural features are positioned to reduce drag forces and ensure the safety of the building occupants in small to moderate wave loading situations.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-0530759 (NEES Research) and CMMI-0402490 (NEES Operations). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the investigators and do not necessarily reflect the views of the National Science Foundation.

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