SURGE IMPACT LOADING ON WOOD RESIDENTIAL STRUCTURES

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Abstract

Current building codes concerning storm surge impacts may be deficient in that they are not based on a robust set of experimental tests. This was most recently made evident during the aftermath of hurricanes Katrina and Rita, when research teams noted many failures in structures that should have been able to withstand the loadings. Clearly a better understanding of these forces is needed, and recent works that show tsunami and hurricane surge damage to be similar provides an even more widespread area for this knowledge to be used. This project aimed to subject a 1:36 scale model structure to surge loading and record the uplift and compression forces experienced at the model's foundation. Wave loading forces were determined from the foundation loadings and compared to estimations made by the Revised Ordinances of Honolulu. Another primary goal of this project was to provide proof-of-concept data and logistical experience for a more comprehensive yet similar NEES project that will follow directly, involving 1:6 scale models and collection of deflection data in addition to loadings. Primary objectives were achieved, showing relative accuracy of Hawaii Building Code predictions and providing a number of recommendations to refine the data collection process of future, similar experiments.

Project Overview

The primary, long-term objective of the NEES Wave Loading on Residential Structures Project is to develop a relationship between the experimental parameters of wave height and damage to a typical woodframe residential structure. This will be accomplished through a two step process. Phase one will consist of 1:6 scale model testing to be conducted at the Oregon State University Tsunami Wave Basin, in which the models will be subjected to breaking waves and bores of varying heights. The models will rest upon four single axis load sensors, one at each corner of the baseplate, so that uplift and compression forces can be observed during impact. In addition, deflection of the structure shall be recorded using displacement sensors, and video cameras will be used to capture images of wave run up and other fluid effects. Once these data have been analyzed and the forces can be effectively scaled, phase two of the project will begin, which will consist of full scale testing at Colorado State University's Hurricane Load Frame. Full scale testing is needed because of the inherent limitations encountered when scaling wood, many of which arise from the irregularities which always exist in the material such as knots and slope of grain. As a result, deformation and force do scale for wood, but damage does not. This also implies that great care must be taken when selecting construction materials and methods for the 1:6 scale models so that the models will respond appropriately when loaded. (Kittel, 1997) Early preparations for the NEES 1:6 scale tests began in the summer of 2007 and testing has been planned to run through December of that same year. The REU project undertaken and completed during the summer of 2007 at the Tsunami Wave Basin served as a small pilot project, providing proof-of-concept data and logistical experience for the 1:6 scale tests.

Figure 1. 1:6 Scale Model House in Construction

Setup

A 1:36 scale wooden house was constructed in order to test the feasibility of measuring uplift and compression forces on the baseplate during wave impact, as well to determine if those measured forces could be used to determine the surge impact force on the leading face of the house. The house was simply constructed from spare lumber and was not designed to deflect as the 1:6 scale models were designed to. This was in the interest of scope and time as this pilot project was only intended to measure compression and uplift forces on the baseplate. The baseplate was intended to be rigid, and as such was cut from a 0.5 inch thick sheet of aluminum. The resulting baseplate was square, measuring 15 inches on a side. The house essentially consisted, geometrically, of a rectangular prism 15 inches long, 7 inches wide, and 7 inches in height, along with a simple, sloped roof on top of it. The house was centered on the baseplate and attached as rigidly as possible with bolts through the baseplate, and in order to maximize the recorded forces, the house was oriented so that the broken waves would impact the structure on its longest face.

The sensors used were 500 pound, single axis load cells, capable of measuring load in both positive and negative directions along that axis. In order to record the uplift and compression forces during impact, the sensors were installed as a mounting system that attached the baseplate to the concrete basin floor. At the time of testing, only three sensors were available, so one was placed at each rear corner of the baseplate, relative to the oncoming wave, and one placed in the center of the leading edge of the baseplate. In addition, a depth gauge was installed near the model in order to measure surge height. This was done by affixing a decal that consisted of a grid of 0.4 inch (1 cm) squares to a piece of sheet metal, which was mounted vertically in the basin via a bracket and anchor bolts. As a surge impacted the model, a digital camera on a tripod was aimed at the depth gauge and captured images that could later be used to determine the maximum height. Though the capture of an image with the camera at the precise moment of maximum surge was unlikely, it was hoped that through the repeatability of the wave generator at the basin that over a large enough number of trials the maximum surge could be determined with sufficient accuracy. Lastly, an ADV (Acoustic Doppler Velocimeter) was installed approximately 5 feet in front of the model in order to measure flow speed of the broken wave, or bore, just prior to impact. An ADV detects velocity by means of sonar, bouncing the signal waves off moving particles in the water and measuring the Doppler shift upon its return.

Method

In an attempt to validate the experiment, it was decided to compare experimental results with some force estimations made by an existing building code that addressed storm surge. The code chosen as the source of these estimations was the Revised Ordinances of Honolulu building code. (http://www.honolulu.gov/refs/roh/16a11.htm) In particular, the following formula for Surge Force was used:

$$F_S = 4.5\ pgh^2 \qquad (1)$$

Where p is the density of water (given as $2.0\ \text{lb-s}^2/\text{ft}^4$ in the ordinances), g is acceleration due to gravity, and h is the height of the surge. It should be noted that this equation yields force per unit width, so to obtain the total surge force acting on a surface, F_S must be multiplied by the width of the surface normal to the approaching wave.

Though used in the building code, it has been noted that this equation may result in excessive overestimations of the surge force. In particular, Dr. Harry Yeh and others in "Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites" (Washing Division of Geology and Earth Resources, Open File Report, Nov. 2005) cite two recent independent experimental studies that demonstrated surge forces well below estimations provided by Equation (1). According to Yeh, both of these studies recorded maximum surge forces that would correspond to a leading coefficient of 1.5 in the surge force equation, as opposed to 4.5. This results in surge force estimates that are a third of the previous estimates. Also worth noting is that in the interest of scope and simplicity, no attempt was made during this project to scale the experimental forces to prototype scale. Instead, the experimental forces were compared to estimations given by (1) for surge height values of 2, 4, and 6 inches, all of which were possible surge heights the model could have experienced. The results from (1) were then multiplied by 15 inches, the width of the model structure orthogonal to the impacting surge. The resulting forces are given in Table 1.

Table 1. Surge Force Estimations

2"	14.04 lb
4"	40.25 lb
6"	90.56 lb

In order to derive the load cell force estimates from the surge force estimates, the 1:6 scale model was considered as a simply supported structure and basic statics was used. The surge force was modeled as a localized load located h feet (height of the surge) above the base of the wall, as prescribed in the Honolulu ordinances. This force was taken to create a moment about the rear (furthest from incoming wave, point B in Figure 2) edge of the house, attempting to rotate it in a cantilever fashion. The moment was then balanced by the load sensor that affixes the model to the basin floor along the front edge. (Force R_A in Figure 2) Though extremely simplified, this became the only viable method due to the time constraints of the project.

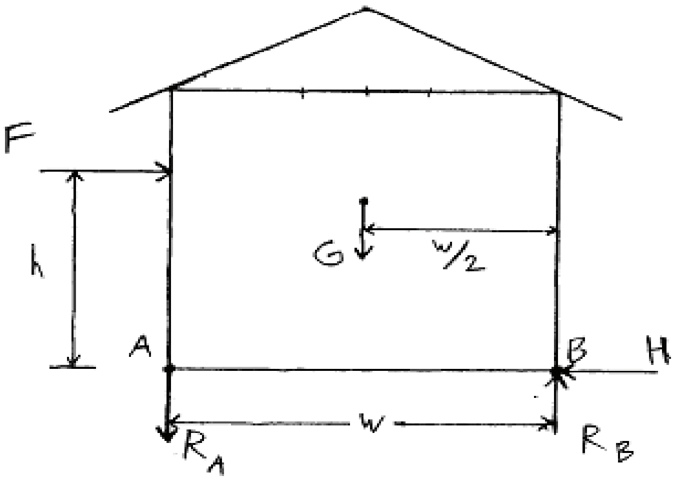

Figure 2. Free Body Diagram of Scale Model

Figure 3. Scale Model

Results

Of the numerous wave heights generated by the Tsunami Wave Basin wave maker during the period of the experiment, a generated wave height of

19.7 inches (50 cm) was selected as the primary source of data for the impact forces. Though the wave height of 19.7 inches was much larger than the total height of the scale model, the resulting bore that was generated by such a wave as it came onshore was much smaller. Through use of the depth gauge, 10 trials were recorded with the digital camera, and the maximum height of the surge during the time of impact was consistently between 5 and 6 cm, or approximately 2 inches. As the total height of the scale model was approximately 7 inches, this surge height fell within the realistic range when compared relatively to full scale surges experienced by structures during tsunami and hurricane events.

During impact, forces experienced by the load cells were transmitted to a data logger and were subsequently exported to a personal computer for analysis. In order to more accurately record the peak forces during impact, the decision was made to record data at the fastest possible rate that the data logger was capable of: one sample every 0.01 second. Unfortunately, in order to obtain this sampling rate, some resolution was lost which resulted in extra noise in the data, as seen in Figure 3.

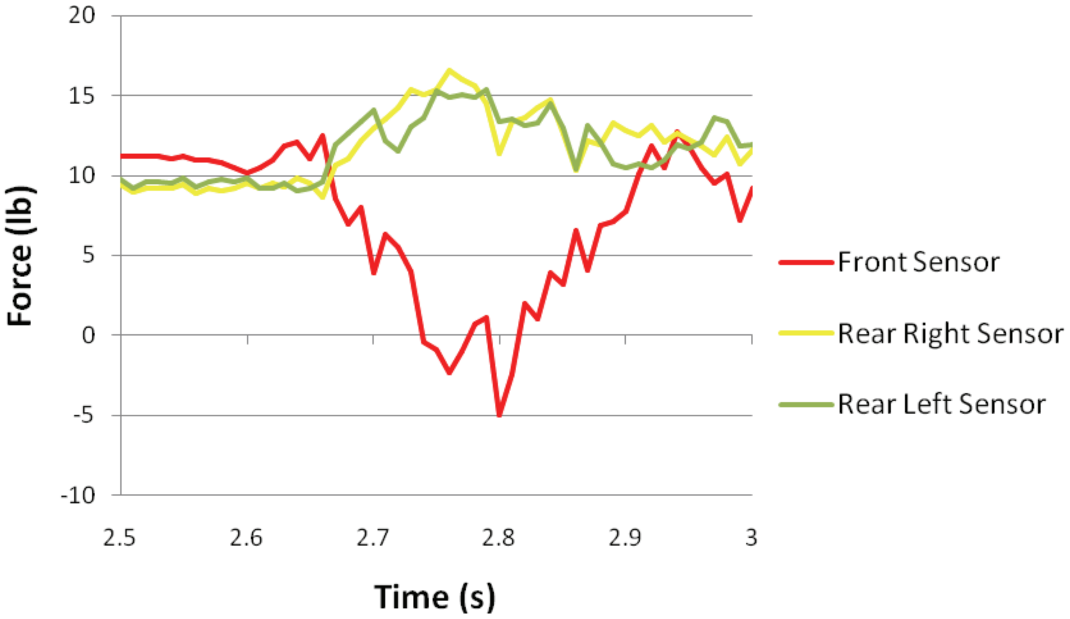

Figure 3. Typical Surge Impact Forces

Though the data points were somewhat erratic, useful information could still be extracted from the graphs in Figure 3, and it was hoped that by averaging the peak force recorded by each sensor over all 10 trials, a sufficiently accurate estimation of peak impact force could be obtained. In Figure 3, increases in force correspond to a sensor experiencing a compressive load, while decreases correspond to a tensile load. As one would expect, the graph clearly shows the rear two sensors experiencing compression and the front sensor tension during impact. Also as expected, the change in load experienced by the front sensor is approximately twice the change in load experienced by each rear sensor, indicating that the total compressive load at the rear of the model is approximately equal to the total tensile load experienced at the front of the model.

Somewhat unexpectedly on the other hand, is the amount of time between initial impact and peak load. As opposed to the peak loading occurring at the instant of initial impact, it occurs a full 0.2 seconds afterwards. Possible explanations for this phenomenon, which was observed in all 10 trials, include the profile of the incoming bore as well the unintended effect of run-up against the face of the house.

After 10 trials, the average peak load experienced by the front sensor was 14.95 lb, in tension. Using the method of statics outlined previously, this reaction resulted in an average peak surge impact force of 45.85 lb. Given that the storm surge height for these trials was approximately 2 inches, this force was unexpectedly and substantially higher than the force predicted by the Honolulu Ordinances.

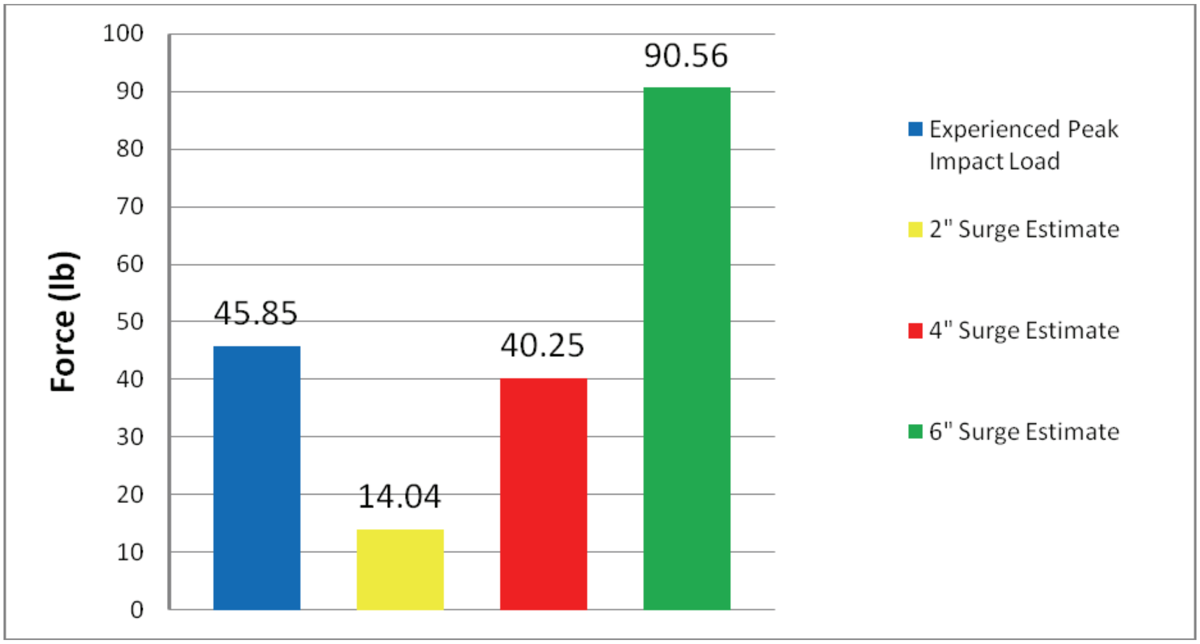

Figure 4. Experienced Load vs. Honolulu Estimates

As seen in Figure 4, the load experienced during the experiment was actually higher even than what the Honolulu Ordinances predicted for a surge of 4 inches, twice the experimental storm surge height. This also contradicts the concerns that the formula used in the Honolulu Ordinances can provide extreme overestimations.

Conclusions

Upon closer inspection of the experimental setup and method, the inflated peak loads experienced could be due to a number of reasons. First and foremost, the Honolulu Ordinance makes no mention and does not take into account the effect of run-up during impact. Upon visual inspection of the surges impacting the model, it was clear that within less than a second from initial impact, the effect of run-up was extreme. Though the height of the unobstructed bore was only 2 inches, the height of maximum run-up against the model was over an additional 2 inches, resulting in a total water height of over 4 inches against the leading face of the structure. It was the author's belief that this run-up effect was the primary cause of the excessive loads that were experienced during the experiment. In fact, if the force estimations were derived solely from the actual height of water against the structure during impact, including run-up, the experimental forces would have been much closer to the predictions. This demonstrates the need to differentiate between simple bore height and full impact height of the water, including run-up.

Another likely source of error was the simple method used to determine the surge impact force from the load cell data. Additionally, the fundamental nature of the surge impact makes it difficult to isolate and accurately measure various forces during impact. During the impact, a host of other forces associated with fluids begin to act on the model, including drag, hydrostatic, and buoyant forces. Though building codes such as the Honolulu Ordinances predict all of these forces distinctly without interaction, isolating and accurately measuring any of these forces in a realistic laboratory experiment in order to test their validity may prove incredibly difficult.

Though these sources of error may be considered detrimental, much was learned from the experiment concerning the nature of studying fluid impact on structures, and in this sense the testing served its purpose. The study of surge impact on scale wooden structures in a wave basin is very much uncharted territory in the field, and many useful recommendations were made for the NEES 1:6 scale tests that were to take place following this REU project. As far as setup, a watertight skirt installed around the baseplate was advised, in order to prevent water from flowing between the baseplate and the basin floor and creating buoyant forces. Any step that could be taken to better isolate the surge impact force should not be overlooked. Also, as is always the case when studying any type of impact, a very high sampling rate is necessary. The sampling rate of one sample per every 0.01 second used during the REU project proved insufficient to get clear data. As a logistical recommendation, the need for quick repairs and/or adjustments to the wooden models should be addressed. A supply of extra fasteners and other construction elements kept on hand during the tests would likely greatly improve the number of successful trials that could be recorded. Overall, this author believes that the future tests involving the 1:6 scale models in the wave basin as well as the full scale tests to be conducted at Colorado State University will be successful and spark much new research in a field that needs much experimental testing.

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Appendix – Sample Calculations

Determination of Surge Loading by use of Statics

From Figure 2, the weight of the structure was not needed since only the change in the sensor readings was used in the calculation. From measuring the model, the front sensor was found to be 11.5 inches from the rear anchor of the structure, and the point of impact of the bore height on the structure was 3.75 inches above the anchor, 2 inches of measured bore above the baseplate of the structure plus 1.75 inches of distance between the anchor point and the top of the baseplate. These measurements and the average experienced change in loading of the front sensor of 14.95 pounds lead to the following calculation when summing moments around the rear anchor of the structure:

$$0 = (14.95\ \text{lb})*(11.5\ \text{in}) - F_S*(3.75\ \text{in})$$

Solving for F_s, the force of the surge, leads to $F_s = 45.85$ lb

References

Kittel, M.R. 1997. Small-scale modeling of metal-plate-connected wood joints. M.S. Thesis, Oregon State University, Corvallis, OR.

Revised Ordinances of Honolulu 2007, http://www.honolulu.gov/refs/roh/