Engineering Structures 31 (2009) 2534–2539

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Tsunami bore forces on a compliant residential building model

John W. van de Lindt [a,*], Rakesh Gupta [b], Rachel A. Garcia [a], Jebediah Wilson [b]

[a] Colorado State University, Department of Civil Engineering, Mail Stop 1372, Fort Collins, CO 80523-1372, USA

[b] Department of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331-5751, USA

ARTICLE INFO

Article history:
Received 31 October 2008
Accepted 17 May 2009
Available online 23 June 2009

Keywords:
Wave
Tsunami
Light-frame wood
Hurricane
Surge
Collapse

ABSTRACT

The forces exerted on light-frame wood buildings as a result of surge and waves are not fully understood. With a better understanding of these types of forces, it may eventually be possible to build coastal structures to better withstand the loads. In this paper, a recent two part experimental study that focused on determining the forces induced in a structurally compliant model of a typical Gulf Coast residential building is summarized. The one-sixth scale building was designed to approximately behave as the full scale building would under wave loading using rules of energy-based similitude. The compliant model was subjected to solitary wave loading in the Network for Earthquake Engineering Simulation (NEES) tsunami wave basin (TWB) at Oregon State University with wave heights ranging from 0.1 m to 0.6 m. Then, at Colorado State University, lateral force–deformation tests on a nominally identical model were performed in order to determine the force–deformation relationship for the building. The structural deformation produced by solitary waves in the wave basin was combined with the experimentally measured deformation in the structural laboratory to determine the force induced by the waves between 0.2m and 0.6 m. Finally, a simplified force equation constant similar to the existing design code formats was found to be 0.31.

1. Introduction

Early civilizations were often formed at or near the coastline for transport and sustenance needs, which is evidenced by the large populations still present in coastal cities worldwide. While water can provide valuable resources, moving water is also one of the most powerful and deadly forces on earth. On December 26, 2004 the second largest earthquake ever recorded on a seismograph occurred off the west coast of Sumatra, Indonesia. The M9.1 earthquake caused vibrations for almost 10 min, also making it the longest earthquake ever recorded. This earthquake triggered what was later to become known as the "Asian Tsunami" coming ashore in Indonesia, this tsunami reached an estimated 10m to 30m and affected regions as far away as Somalia. The United Nations reported that an estimated 229,866 people were lost (missing or deceased) with over one million people displaced. In addition to tsunamis, hurricane surge and waves cause tremendous damage to coastal infrastructure. Hurricane Katrina ranks as one of the deadliest and costliest natural disasters in US history. Formed on August 23, 2005, it made landfall as a Category 3 hurricane on August 29th and devastated the US Gulf coast region. It was estimated that 1836 people lost their lives in Mississippi, Louisiana, Alabama, Florida, Georgia, Kentucky, and Ohio as a result of wind, surge, and flood.

Although coastal structures continue to be devastated by hurricane surge, waves, and wind, people continue to re-build along the eastern seaboard and Gulf coast of the US, as evidenced by the 2007 population in Biloxi, MS, which is at 98% of its pre-Katrina population [1]. Thus, it is imperative that the interaction between water, whether from a hurricane wave or a tsunami, and residential buildings be better understood. Wave and surge damage often results in the complete destruction of woodframe buildings and thus little is left for analysis and interpretation. However, if load transfer and shear forces that result from wave loading can become better understood, it follows that innovations may be able to be developed that can allow the building to remain standing and continue to at least provide life safety to the occupants should they choose to vertically evacuate, e.g. move to roof level. It is not the objective of the work presented here to attempt to design wave resistant houses, but rather to provide a basic understanding of the forces imparted by a tsunami wave bore borne from waves of various heights on a typical coastal residential woodframe building. To limit the introduction of error due to scaling issues associated with hydrodynamics, and focus on the forces developed in the building as a result of the wave loading, the results in this paper are reported at the one-sixth model scale.

To date, the majority of studies have investigated the effect of waves on vertical walls such as seawalls. Only several studies

* Corresponding author. Tel.: +1 970 491 6605.
E-mail address: jwv@engr.colostate.edu (J.W. van de Lindt).

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doi:10.1016/j.engstruct.2009.05.017

have investigated the effect of broken waves on vertical walls (e.g. [2–4]). In fact, most wave basin models have been rigid models with pressure taps on the wave loading side of the structure. In the study presented in this paper, the building is a one-sixth scale residential structure designed to deform laterally approximately one-sixth the amount of its full- scale prototype. Thus, the key to this study is that the model is compliant, i.e. moves approximately to scale with wave impact. It is hypothesized that this movement, although relatively small, results in internal forces less than those that would be computed using the combinations of pressure taps and tributary area on a rigid model. The basic concept of this study can be summed up in several steps whose details are expanded on in the remainder of this paper:

Step 1: Develop a numerical model to approximate the compliant (load-deformation) behavior of the full-scale (prototype) house.

Step 2: Build one-sixth scale house models.

Step 3: Perform wave basin tests on the one-sixth scale model in the tsunami wave basin at Oregon State University. During these tests the lateral displacement of the building is measured for each wave height.

Step 4: Perform structural laboratory tests at Colorado State University to determine the load-deformation relationship for the house.

Step 5: Combine the load-deflection relationship determined in Step 4 with the deformations measured in Step 3 to determine the force in the building as a result of each wave height.

Step 6: Based on a simplified force per unit length equation format, compute a force constant for the force in the building as a function of wave height.

2. Design and construction of compliant residential model

Initially, a simple floor plan was selected that (1) was thought to be representative of a two-story residential building along the US Gulf coast; and (2) had significantly different dimensions on each side so it could be turned 90 degrees during testing, essentially providing two datasets. This would also help average the effects of normalizing the forces in the building by width. Fig. 1 shows the one-sixth scale building floor plan with dimensions in metric appearing in brackets. The building was designed as a three-bedroom house with a one-car attached garage with approximately 186 m^2 (2000 ft^2) of floor space. Throughout this study, no effort was made to include non-structural finishes such as gypsum wall board (drywall) or exterior siding. Because the focus of this study was on the forces induced in the building and not necessarily on the ultimate capacity of the building, this approach was felt to be justified. The geometric scale factor was determined based on the size of the wave that could be generated in the tsunami wave basin (TWB) at Oregon State University (OSU). Specifically, a 0.6 m wave was able to be produced in the three dimensional TWB. This approximate scale factor was then used in the development and design of the structurally compliant residential building model.

The lateral force–deformation behavior of light-frame wood buildings is governed primarily by shear wall behavior within the building. In turn, the shear wall behavior is governed by the fastener (nail) behavior as a group. Thus, it was thought that if a single nail could be scaled to behave approximately as a one-sixth scale connection, then the assembly of the one-sixth scale walls and the entire building could simply be geometrically scaled. In order to do this, a number of very small nails, tacks, and staples were tested using the displacement control protocol shown in Fig. 2. However, the behavior of a connection in shear and the corresponding hysteretic models being used within the software (discussed below) necessitated the reversed cyclic test. Practical reasons related to construction and sheathing thickness did not allow smaller nails to be considered, and larger nails dissipated too much energy for similitude. Therefore, an alternative approach was selected. Recall that while the behavior of a wood shear wall is governed by the fasteners, the behavior of the building is governed by the shear wall behavior. In other words, if the nails within each shear wall assembly could be positioned to enable the one-sixth scale wall model to behave as a scaled version of the full scale wall prototype, when assembled together they should approximately reproduce the system level lateral behavior. Also recall, the objective of designing the structure to be compliant at one-sixth scale was to allow it to move in a manner similar to a full scale building and dissipate impact energy.

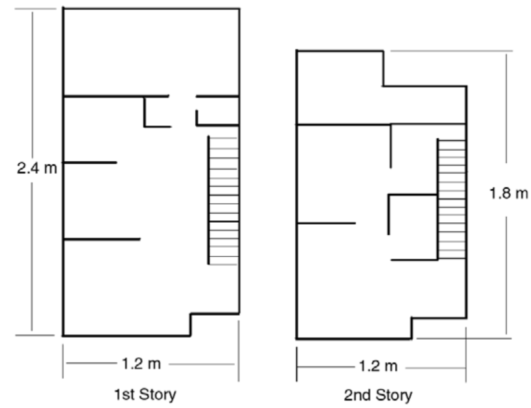

Fig. 1. Floor plan of one-sixth scale model.

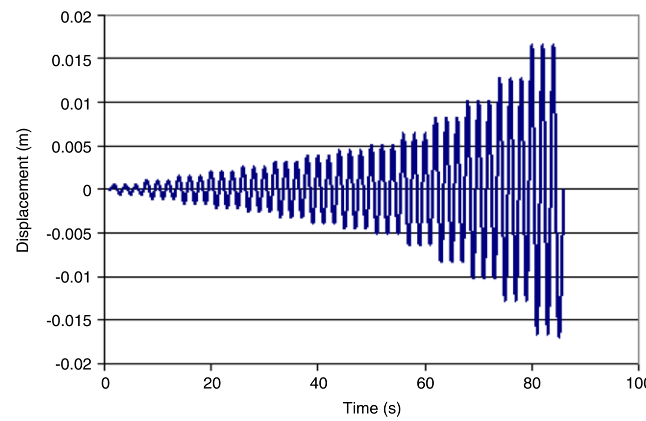

Fig. 2. Reversed cyclic displacement control protocol used for nail testing.

This later approach was selected and each shear wall assembly was modeled in an existing software package, SAPWood [5]. Fig. 3(b) shows the pushover curves for wall assembly S2-A (see Fig. 1 for wall location), whose layout is shown directly above in Fig. 3(a). The full scale model has nail spacing of 150 mm around the outside of the sheathing panels and 300 mm on the interior studs, i.e. field nailing. It should be noted that while the stiffness differs between the scaled-up model and prototype, they are clearly on the same order of magnitude. Scaling wood connections at this level is extremely difficult as one can see from Fig. 3(b). It was decided that the roof and floor diaphragms would be designed to be very rigid in order to allow the focus of the testing to be on the lateral deformation and behavior resulting from the wave loading. The roof system was created using dimension lumber cut down to 12 mm by 18 mm. The roof trusses were designed to be similar to those of the conventionally built residential buildings with two angled members and a single interior supporting member. Several different size roof trusses were constructed to cover the varying widths of the building. The roof system was sheathed in 7 mm thick

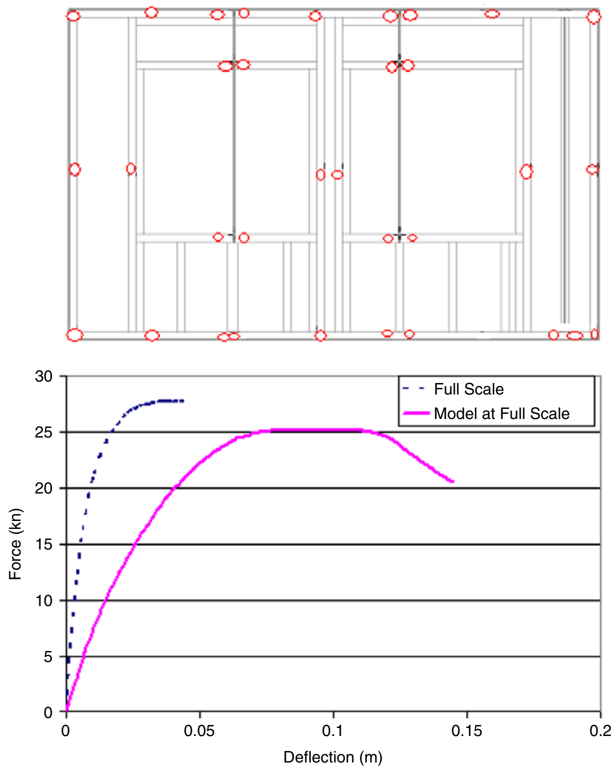

Fig. 3. Comparison at full scale between the one-sixth scale model and the prototype (both shown at full scale) based on the SAPWood model prior to testing.

plywood for very high stiffness at model scale in order to prevent roof failure. The floor diaphragm consisted of wood cut to 12 mm by 38 mm and sheathed in 7 mm thick plywood on both sides. The floor joists run in the short direction of the building throughout at 65 mm on center.

The anchor bolt locations were designed in accordance with [6] for 130 mph, exposure B, residential light-frame wood construction in high wind areas. This resulted in very close spacing at model scale if geometric scaling was used. Therefore the anchor bolts were placed between every other stud which yielded a spacing of approximately 125 mm and bolts that were slightly larger than those required for uplift and shear force similitude were used which essentially fixed the base of the building to its foundation. Stainless steel 3.5 mm diameter bolts were used as the scale model anchor bolts. A 12.7 mm thick steel plate was used as the structure's foundation. The uplift (or tensile and compressive) reaction forces to wave loading were recorded using four load cells located under the four corners of the steel foundation plate. The load cells were then set down on washers and bolts embedded into the concrete floor of the wave basin.

3. Wave basin testing

The wave test series was performed over the course of approximately two months for a total of six days of testing and details can be found in [7]. In this paper the focus is on two configurations which were felt to be the most generic of the tests and thus best data for determination of the wave force per unit width for a building. These two configurations were (1) short side of the building facing waves, and (2) long side of the building facing waves. The windows were covered making the object in the path of the wave simply a rectangular body. The loading was applied as a solitary wave (a single wave of specified height) but with an artificial concrete reef positioned such that it resulted in the wave breaking prior to making contact with the model. This reef was part of the concrete floor in the tsunami wave basin and resembled the Oregon coastline. Fig. 4 shows a series of photos taken in (1) still water; (2) as the wave bore approaches the model building and (3) during impact. The wave heights used for testing ranged from 10 cm to 60 cm in increments of 10 cm. The order in which the wave heights were applied, and the number of waves at that height, varied from day to day. Within this paper the averages for each dataset are presented.

The data set used in this paper was recorded when the water height came just to the top of the steel plate under the model. As mentioned, the model building was turned so that it had the short side facing the oncoming wave (hereafter referred to as orientation A) and the broadside facing the oncoming wave (hereafter referred to as orientation B). During each test the displacement at the top of the second story was recorded during wave impact using a LVDT. Fig. 5 shows an example of the recorded lateral displacement of the building during testing. Fig. 6 shows the maximum lateral displacement of the building as a function of wave height. As can be seen by the data points in Fig. 6 there were a varying number of tests for each wave height for orientation A (short side facing on-coming waves). In addition, several of the 10 cm waves broke either just in front of the building model or actually into the model and it was therefore decided to only utilize the data between 20 cm and 60 cm for orientation A. The dashed line in Fig. 6 shows the overall trend in this limited region. Fig. 7 presents the maximum displacement of the building model for orientation B. Note that the majority of the tests were performed at wave heights of 20 cm and 40 cm for orientation B. No data was available for the 60 cm wave at orientation B. It was observed that the main impact of the wave encompassed the first story and only a small amount of runup and spray affected the second story.

4. Wave force calculations

In order to calculate the forces in the model during wave impact a force deformation curve was determined experimentally at the structural engineering laboratory at Colorado State University. The model tested in the structural laboratory was nominally identical to the model in the wave basin. Although the building was designed

Fig. 4. Typical sequence photos of wave impact during TWB testing. The photos shown here are for a 50 cm wave.

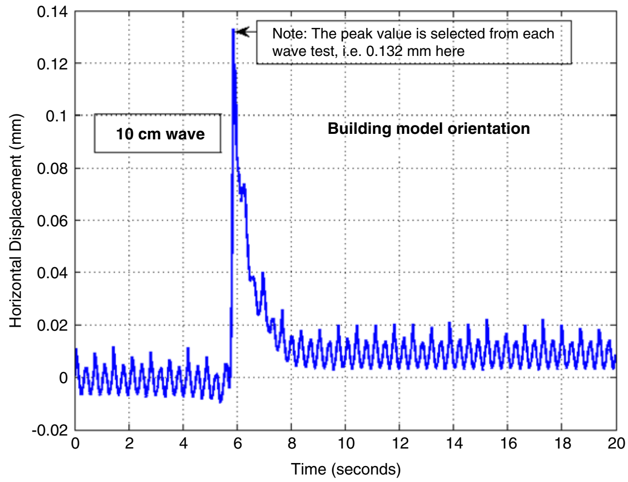

Fig. 5. Example of the Measured Horizontal Displacement during Wave Impact.

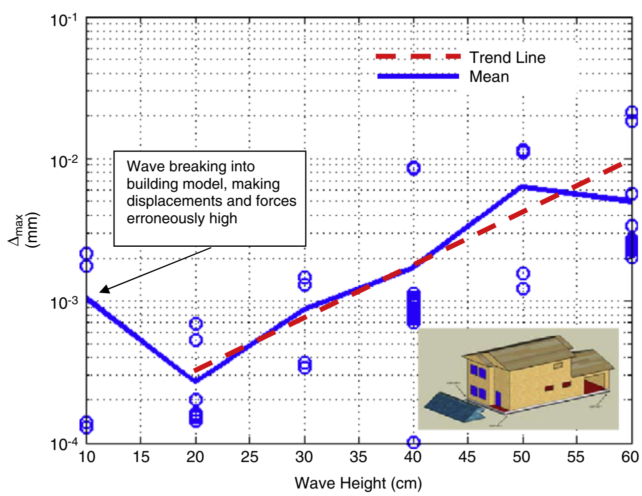

Fig. 6. Maximum Lateral displacement of the building in Orientation A as a function of wave height.

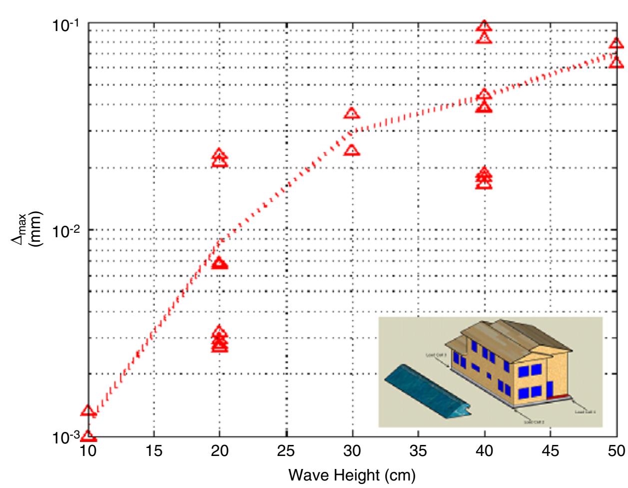

Fig. 7. Maximum Lateral displacement of the building in Orientation B as a function of wave height.

to perform based on similitude, it was not felt that this was accurate enough at one-sixth scale to back the shear force out from displacement measurements, particularly because of the difficulty in scaling a light-frame wood building (even at half-scale) (see [8] for details). Therefore, a specimen which was nominally identical to the model tested in the TWB was tested using the test setup shown in Fig. 8. As one might expect, during wave impact it was observed that the wave impacted only the first story and then ran up the side of the model, depending on the wave size. However, even for the largest waves the runup was not significant on the second story. Thus, it was decided to place a small hydraulic actuator at the top of the first story during the structural laboratory test. This would allow the first story level to deform in shear and the second story to remain unloaded since it was clear from the photograph in Fig. 9 that the building failed in shear on the first story level. The structure was pushed only enough to determine the initial stiffness and curvature as shown in the experimental force–deformation curve in Fig. 10.

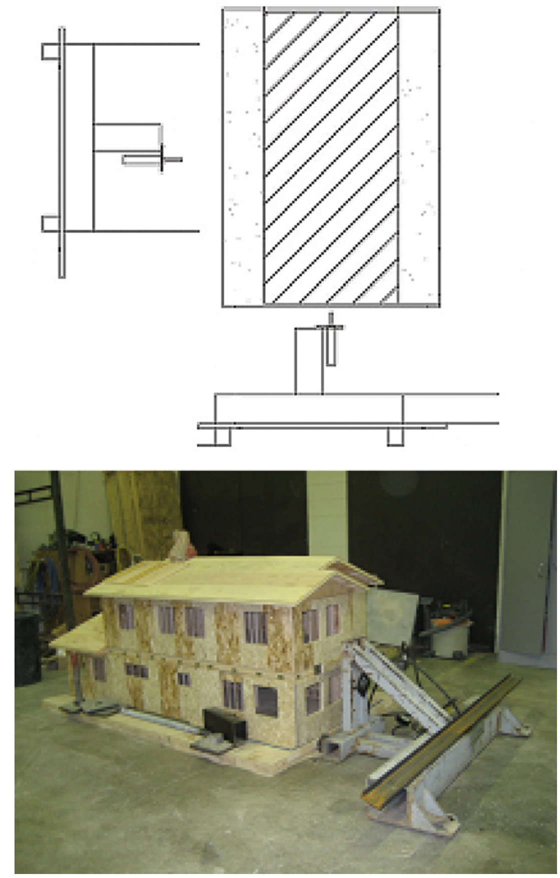

Fig. 8. Experimental setup at Colorado State University for determination of the load–deformation curve.

The dashed line in Fig. 10 represents the original SAPWood numerical model which was significantly weaker and softer than the model building, further underscoring the difficulty with scaling wood at this small scale. This may also be exacerbated by the flanging affect (the effect of the wall perpendicular to a shear wall acting similar to the flange of a beam) the transverse walls located at the ends of shear walls this effect occurs to a much lower extent in full scale wood frame buildings, but seems to be very noticeable at this scale. Systematic adjustment not detailed in this paper, but available in [9], was then made to the numerical hysteretic shear wall models to essentially calibrate the numerical model. The numerical force- deformation relationship shown in Fig. 10 was then used to determine the corresponding shear force in the model building. The shear force in the model was then determined directly from Fig. 10 simply by identifying the shear force in the structural test building that corresponds to the horizontal displacement measured during the wave basin test. It should again

Fig. 9. Collapse of model in orientation B when subjected to the 60 cm wave. Note that there was 10 cm of standing water in and around the building. This water was not present during the majority of testing including the data used to determine the force equation constant in this study.

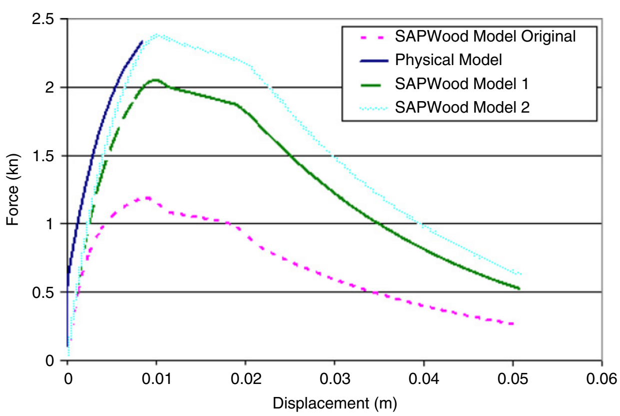

Fig. 10. Comparison of the calibrated SAPWood model and the experimentally determined load–deformation curve. The curve shown by the dotted line was then used to determine what internal forces were present in the model during wave impact.

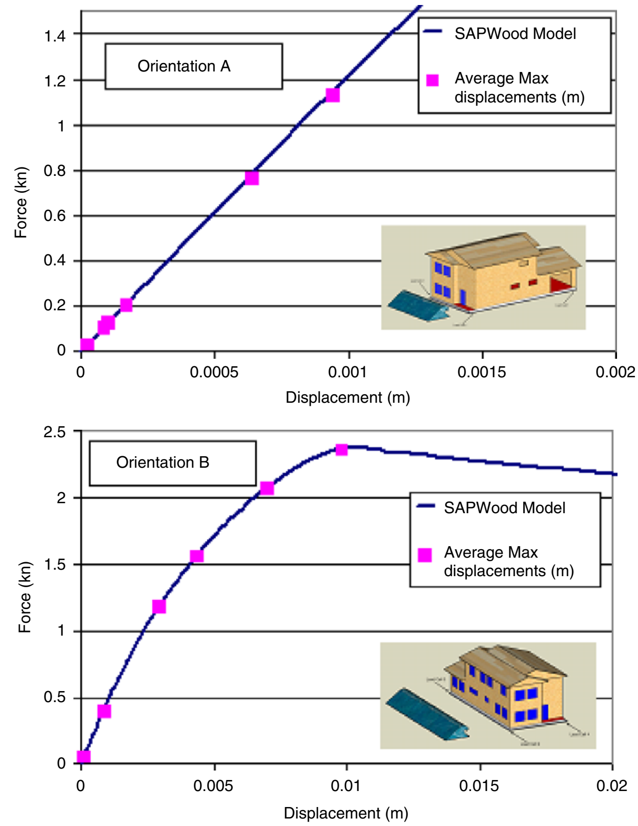

Fig. 11. The maximum lateral deformations recorded during wave impact for the 10 cm to 60 cm waves. Note that each point on the load-deformation curve represents an average of two or more wave tests.

be noted that mean values from multiple tests were used since a wave, even generated in a wave basin, is essentially a random process.

The forces corresponding to the displacements measured in the wave basin are presented in Fig. 11. It is interesting to note that in the lower window of Fig. 11, the ultimate lateral capacity of the model was very nearly reached by the 60 cm wave. As mentioned earlier, the photograph shown in Fig. 9 depicts the same 60 cm wave but with the still water level 10 cm higher. Thus, one can qualitatively assume that with 10 cm more water at base level, the shape of the shear force distribution was altered and the capacity of the first story of the model was exceeded. This evidence, while somewhat circumstantial, supports the accuracy of the shape of the SAPwood model calibrated and presented in Fig. 10.

A very simplified approach to estimating the force from the bore created by the leading edge of a tsunami appears in the Article 11 of the Honolulu Building Code in the following form

$$F_s = c\rho g h^2 \tag{1}$$

where F_s is the surge force per unit length, c is a constant to be determined from data, ρ is the density of salt water, g is the gravitational constant, and h is the surge height. Rearranging Eq. (1), and using wave height, h_w, instead of surge height, the code constant, c, can be expressed as

$$c = \frac{F_s}{\rho g h_w^2}. \tag{2}$$

As mentioned, rather than investigate the value of c for the height of the bore, h_w was modeled as the height of the wave generated by the wavemaker in the TWB, i.e. prior to breaking and becoming a bore. The reason for this was that in model studies there is significant control over height of the generated wave, but much less with regards to the wave bore which is turbulent. Fig. 12 presents the average force calculated from the load response curves, based on building orientation, for each wave height. Note that as discussed earlier these are averages for more than one test at a particular wave height. Then, the values calculated for F_S were determined using Eq. (1) for each orientation and for multiple tests. For example, for the 20 cm wave height there may have been five tests in model Orientation A and four tests in model Orientation B. Depending on the model orientation, each value of F_S was then normalized by the width of the model perpendicular to the path of the oncoming wave, e.g. nine values of F_S total for the 20 cm wave height. A value of c was then computed for each of these values regardless of orientation since they are now reduced to a force per unit length. Fig. 13 presents the average value of c calculated from Eq. (2) as a function of wave height prior to breaking and becoming a wave bore. The consistency for the 0.1 m high waves was, at times, questionable because these smaller waves often broke very close to the structure and twice were observed to actually break into the structure. Thus, these were eliminated from the calculation of an average value of c across multiple wave heights since the bore resulting from these small wave heights was felt to be very unstable. Based on the results presented herein, the experimentally determined constant was approximately 0.31 shown by the bold horizontal line in Fig. 13.

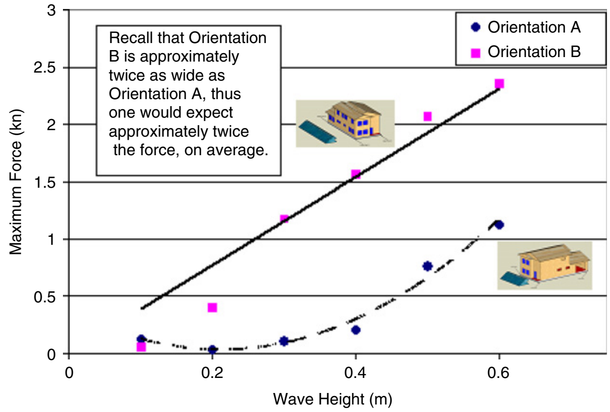

Fig. 12. Force (by test building orientation) as a function of wave height based on the load–deformation curve in Fig. 8.

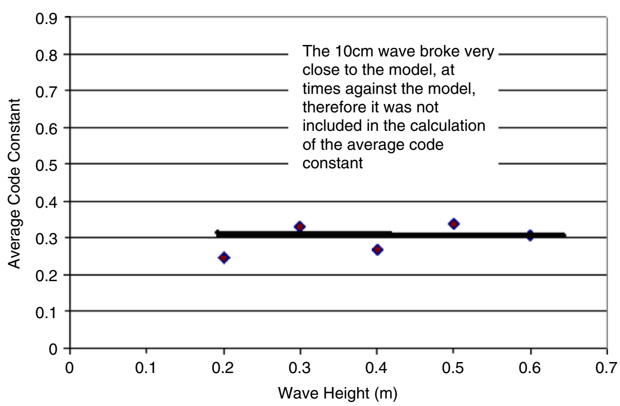

Fig. 13. Constant for Eq. (2) with linear fit shown between 0.2 m and 0.6 m.

5. Summary and conclusions

In this paper a typical two-story wood frame residential building was designed to approximately behave as a full scale building would under wave loading with the aid of an existing software package, SAPWood. The one-sixth scale model was tested in Oregon State University's tsunami wave basin (TWB) for a range of solitary waves and the lateral displacement of the building measured for each wave impact. Then, an experimental load–deformation relationship was determined for a nominally identical one-sixth scale model in the Colorado State University structures laboratory. By combining the experimentally measured lateral displacements and determining their location on the force–deformation curve, the shear force in the building could be estimated. This included a reasonable assumption regarding the location of the loading, i.e. the top of the first story level. Based on this information, a simplified force equation constant was determined for waves between 0.2 m and 0.6 m for the building and was found to be approximately 0.31.

While the procedure summarized herein has several assumptions associated with it, it represents the first three-dimensional wave tank tests on a structurally complaint light-frame wood building. It is further theorized that the motion of the building upon impact does not allow the wave to induce the same forces internally to the structure that would be measured if pressure transducers were mounted to the face of the building being impacted by the wave. It is recommended to continue examining the effect of compliant buildings to gain more insight into the interaction between ocean waves and residential structures with the future objective of providing mechanisms to improve life safety for tsunami hazard.

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. The authors are also grateful to the PBTE NEESR Project Group and the NEES@OSU site personnel for their cooperation and assistance, respectively. In addition, prefabrication of the structural models was performed by Mr. Doug Allen, an undergraduate research assistant. Mr. Milo Clauson provided instrumentation and DAQ expertise during the project. Their skill and participation on the project is acknowledged and appreciated.

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