Real Tsunami Load and Comparison to Earthquake Load Used for Design

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SUMMARY:

After the 311 earthquake in Japan, Tsunami load for design code became a remarkable point in the world. This paper reported our recent research results for Tsunami load. An independent house destroyed by the 311 Earthquake near the Arahama region has been chosen for study. A scale-down model of the two-story house has been tested by shaking table experiments and wind tunnel experiments, and the results by experiments and FEM simulation including inverse calculation of Tsunami force have been compared for establishment of the Tsunami Load.
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Keywords: Tsunami Load, Bending Bolt, Shaking table, Wind tunnel, Simulation.

1. INSTRUCTIONS

1.1. Purpose

During the 20110311 earthquake off the Pacific coast of Tōhoku (The 311 earthquake in short), Japan, many buildings have been carried away by the earthquake-caused Tsunami wave. Although in USA and Japan the Tsunami loads have been suggested for building design in ocean side region, there are still no legal code for designing. Many designers have to follow the earthquake resistant code for their building even the buildings are to be built in Tsunami region and such fact may turn to be the direct reason that many buildings having been carried away in the day of 20110311, because it is believed that the Tsunami loads are larger than the earthquake one.

In general, a real Tsunami load includes the following 3 terms. The 1st one is the hydrostatic pressure which comes from static fluid and acts on the building like lateral pressure. The 2nd one is the dynamic pressure from the moving fluid in which the value of the pressure is dependent on moving velocity of the fluid. The 3rd one is the impulsive force caused by the floating wreckage carried by the Tsunami wave.

The important thing turns to be how to establish Tsunami Load for code. In Japan, Okada et al had presented a method to calculate the Tsunami Load in which the basic consideration of the load is 3 times in height of Tsunami wave and 3 times of the hydrostatic pressure at the bottom of the fluid.

Other researchers have carried out open channel flow experiments to simulate the Tsunami flow, by adjusting the parameters of the water pressure to find new method for Tsunami load or just to verify Okada's method. But unfortunately until now their contributions have not been verified by real Tsunami and real Buildings.

The purpose of this research is also the establishment of Tsunami load, but an independent way has been adopted for simulation. Real data we recorded soon after the Tsunami attacked the Asahama Beach in Sendai City have been used for this research. All Data have been recorded and investigated from the middle of March of 2011, which means the data are fresh and native for Tsunami load. The Arahama Beach has lost 800 houses (nearly 100%) and more than 180 lives during the 311 Tsunami.

A model house has been chosen for this paper and the following substances are to be reported. Models have been made for shaking table and wind tunnel experiments. Shaking table will tell us the differences between earthquake and tsunami load and the wind tunnel experiment will tell us the best direction of the house for reduction of Tsunami load and the comparison between wind load and Tsunami load. Simulation has been presented to make clear the load degree the house having been carried away and, inversely the simulated real Tsunami load by using the bending direction and the shear of the remained bolt of the building.

1.2. Survey of the house carried away by tsunami during 311

Details of evidences of 5 houses had been investigated and measured in the Arahama region. The owners of the houses all agreed our research group to use real data of their houses for study. In this paper only one house shown in Fig. 1 has been chosen for this report. Made from light steel frame, the 2F, 7m in height house located about 350m far away from the ocean shown in Fig. 1. After the Tsunami, only the foundation remained which is shown in Fig.2. And also in Fig. 2, from the tree's falling direction the Tsunami wave direction can be easily confirmed.

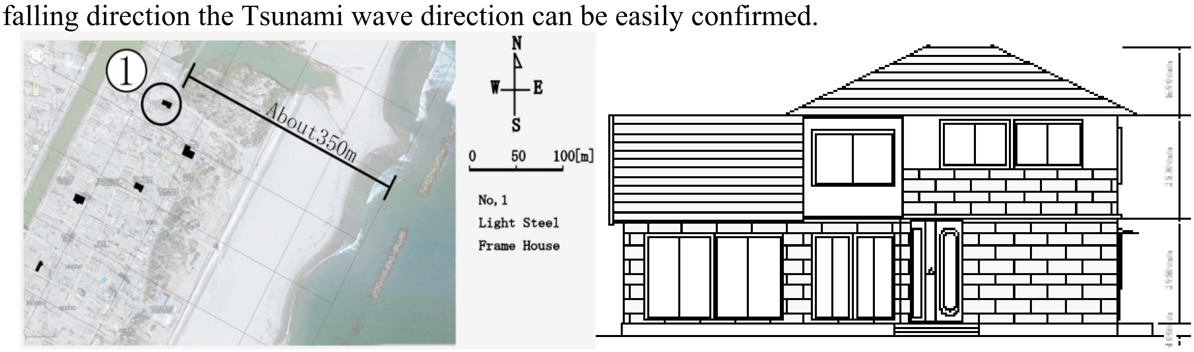

Figure 1. The house is 350m far away from the ocean

Figure 2. Foundation of the building after tsunami

1.3. The evidences for tsunami load = the deformed bolts and remained parts

Detailed measurement of the house clearly shows the following 3 important point for while we wish to calculate the Tsunami load.

A: Because a few part of wall remained which can be found in Fig. 3, it is concluded that the maximum resistant force of the house is just equal to the Tsunami force acted on the house to carry away it, such fact clearly tell us the house resistant force is the Tsunami Load. In other hand if only foundation being left without any parts, the wave force is larger than the house resistant force.

B: Because the bending directions of all the bolts measured are same, we concluded that this building has been destroyed and carried away by the leading wave of the tsunami, not a drawback wave. Such fact will make it simple to simulate the Tsunami load. In some other cases we measured in same region, the bolts left bended to nearly all the directions, which means that the building has been destroyed by both the leading and drawback wave.

C: The bolt remained in the foundation shown in Fig. 3 has been bent and in the same time sheared. The failure force of this bolt is suggested as to take minimum value of the bending or/and shear which is a rule we determined to simulate the Tsunami load..

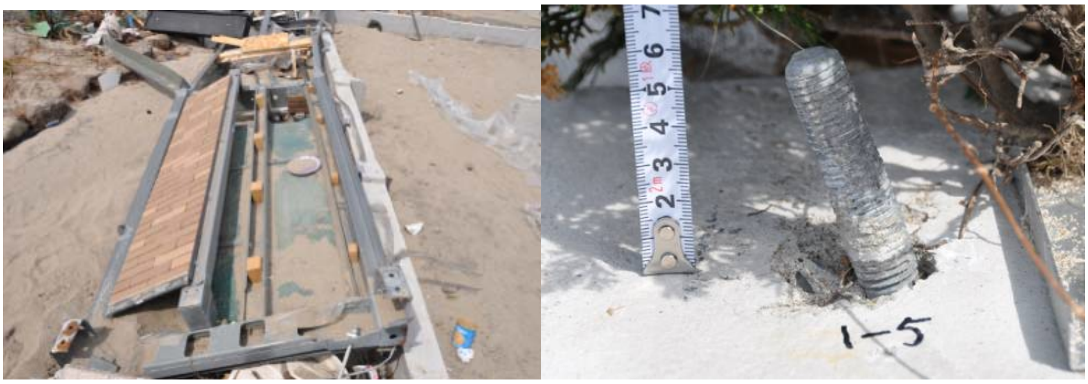

Figure 3. Deformed bolt and remained parts

2. SHAKING TABLE AND WIND TUNNEL EXPERIMENTS

2.1. Shaking table experiment

The purpose of shaking table experiment is to make clear the difference between the earthquake resistant force and the Tsunami force. Considering the size of the shaking table in the Tohoku Institute of Technology (TOTECH), a reduction ratio of 1/17 model shown in Fig. 4 had been assembled, where the 1st natural frequency is 0.51s and the damping factor is 1.775%, obtained from experiment. Not only the 311 earthquake wave recorded in the campus of TOTECH but also other famous waves have been used for the shaking table experiments. From the obtained spectral the maximum stresses for the model have been calculated and are shown in Table 1. If compared with the maximum value of simulated Mises stress from Tsunami (which will be shown in next section), the difference reached about 1000 times. It may become the reason the house escaped from the 311 earthquake but destroyed by the Tsunami wave.

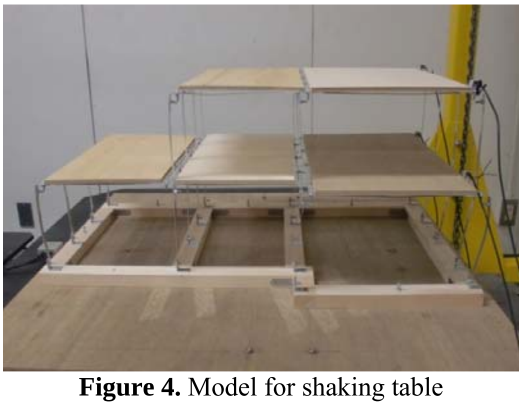

Figure 4. Model for shaking table

Table 1. Shaking table results

Earthquake	Direction	Spectral N/mm^2	Max Stress N/mm^2
EL-CENTRO	NS	5.850×10^{-2}	9.980×10^{-2}
Kobe	NS	9.597×10^{-2}	0.135
Kashiwasaki	NS	5.153×10^{-2}	9.821×10^{-2}
Hachinohe	EW	4.923×10^{-2}	6.007×10^{-2}
311(TOTECH)	EW	0.318	0.496

2.2. Wind tunnel experiment

The purpose of wind tunnel experiment is to understand how wind flow (similar to the Tsunami flow) acting on a house, including the strength and the direction. In other words, in which direction the pressure from the same wind will become maximum or minimum.

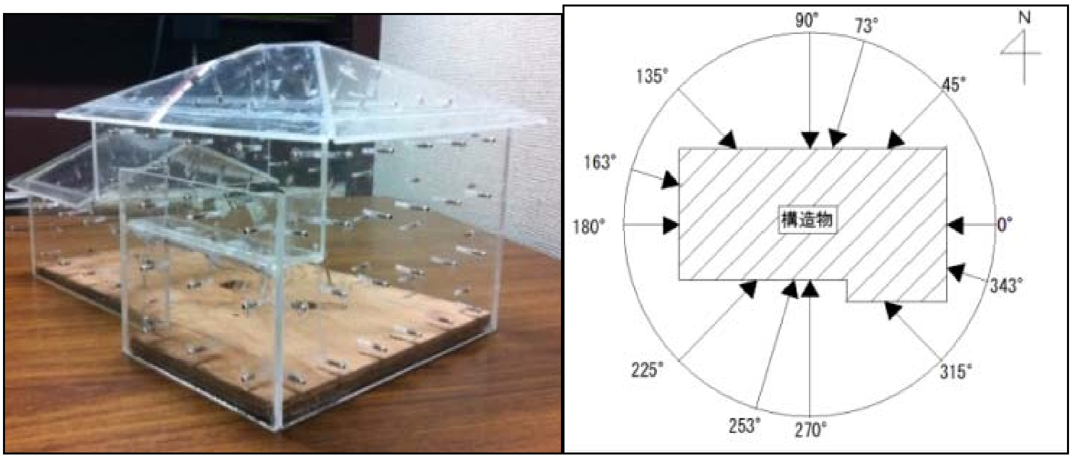

Figure 5. The model for wind tunnel

Table 2. Coefficients of wind force

direction	aspect area（㎡）	coefficient of wind force($\times10^{-2}$)
EW	2.478	28.02
NS	2.478	-7.008
EW	4.333	14.95
NS	4.333	-24.11
EW	4.368	6.429
NS	4.368	-27.21
EW	3.283	-5.433
NS	3.283	-36.30
EW	4.145	-7.858
NS	4.145	-32.62
EW	3.762	-15.83
NS	3.762	-20.76
EW	2.478	-22.22
NS	2.478	1.431
EW	4.331	-9.897
NS	4.331	27.64
EW	4.368	-4.362
NS	4.368	25.51
EW	3.283	0.525
NS	3.283	38.49
EW	4.528	9.402
NS	4.528	12.53
EW	3.762	21.15
NS	3.762	4.296

Fig. 5 is the model for the wind tunnel experiment with reduction ratio 1/50 to fit the size of the wind tunnel in TOTECH. The ground roughness in ARAHAMA region is the 2nd level in Japanese code which determines the vertical wind velocity distribution shown in Fig. 6. Table 2 shows the coefficient of the wind force from the experiment for different direction. It is clear that for 270° NS, the coefficient is about 38.49×10-2, the minimum one is 270° EW, 0.525×10-2. That means if we build the house in the direction of 270°EW, the house may not be flowed by the Tsunami wave during 311. Compared with the results shown in the following section, we understood that the Tsunami force is about 100times compared to the wind force in the case of wind velocity of 60m/s which is nearly the Tornado wind velocity.

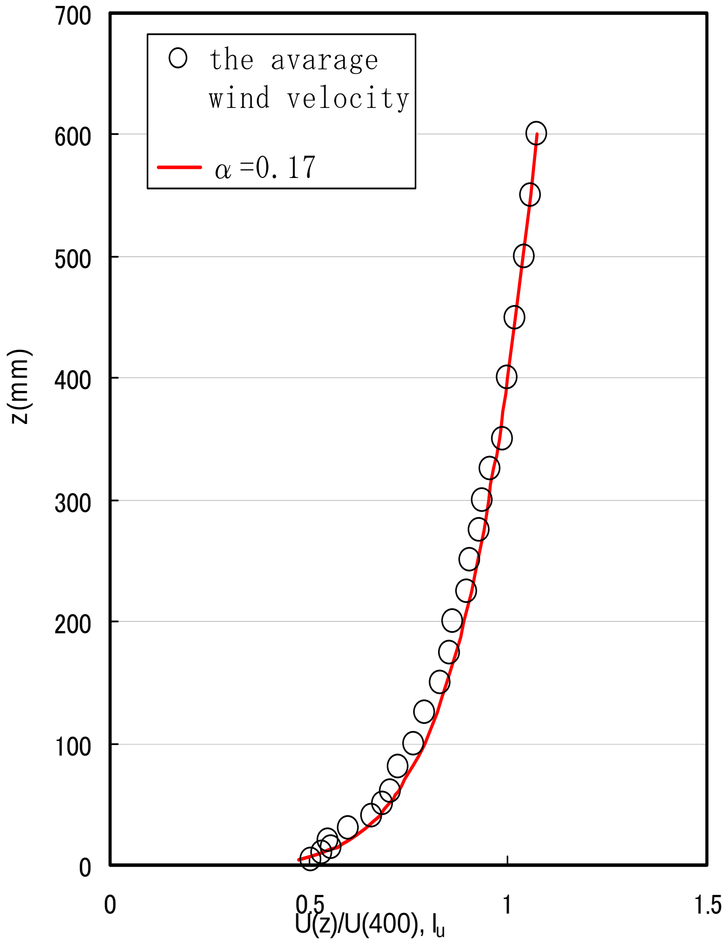

Figure 6. Vertical wind velocity distribution (Normalized Wind Velocity v.s. Height)

3. TSUNAMI SIMULATION BASED ON JAPANESE GUIDANCE

FEM soft Abaqus has been used to build the simulation model for the house, which is shown in Fig. 7, where the material parameters of the column, beam and wall are shown in Table.3.

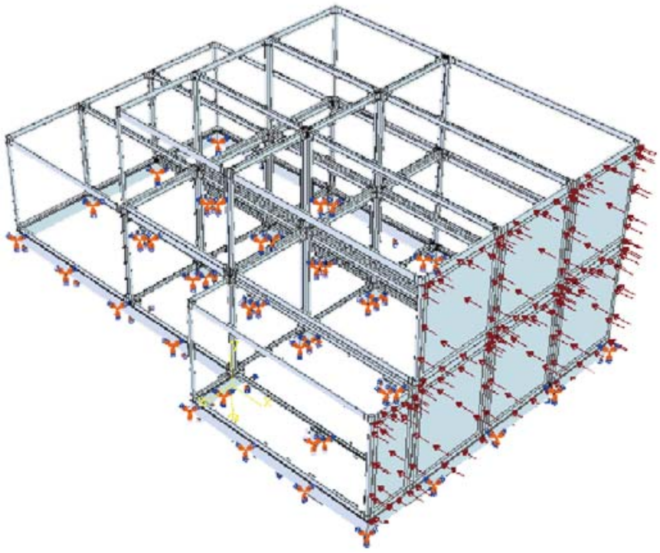

Figure 7. Simulation model

Table 3. Parameters of the material

	Column（Steel）	Wall	Foundation (RC）
Density	$7850\times10^{-6}t/mm^3$	$2000\times10^{-6}t/mm^3$	$2643\times10^{-6}t/mm^3$
Young's Modulus	$2.1\times10^5 N/mm^2$	$1.5\times10^4 N/mm^2$	$3.1\times10^4 N/mm^2$
Possion ratio	0.3	0.3	0.2

Asagura's method for Tsunami Load has been used in our simulation where the load is assumed to be 3 times the hydrostatic pressure, not only for the height but also for the pressure at the bottom. The real Tsunami height in Arahama region in 311 follows the investigation result of research group, Waseda University, to be chosen as 9.38m. The relative story displacement of the simulation has been calculated. Because the house without the roof has a height of 6210mm, and when the relative displacement reached 31.05mm (1/200 of the house), the house is assumed to be destroyed. Based on this we obtained that the load of 9.38m height Tsunami is about 1.214 times the destroy load as shown in Table 4.

Table 4. Calculated damaged stress by code

	Tsunami wave Pressure level(mm)	Tsunami load (N/mm2)	Horizontal Displacement (mm)	Drift angle	Von misses Stress (N/mm2)
Asakura's	28140	0.2758	37.74	0.00608	4313
The building standards law		0.2272	31.05	0.005	-

4. INVERSE ANALYSIS FOR TSUNAMI LOAD

During the site investigation, large plastic deformation of bolts was observed as shown in Fig. 3, the displacement of bolt head went up to about 14mm, providing valuable insights into the Tsunami load. To calculate the Tsunami load inversely from the deformation of bolts, the house is reduced to the following walls and bolts model, with each wall pined to the foundation by a designed number of bolts. Tsunami load is applied as static surface pressure at the front wall, the displacement of bolt head is controlled to reach 14mm. The reaction force satisfying such a displacement criteria is deemed as a reasonable approximation to the Tsunami load.

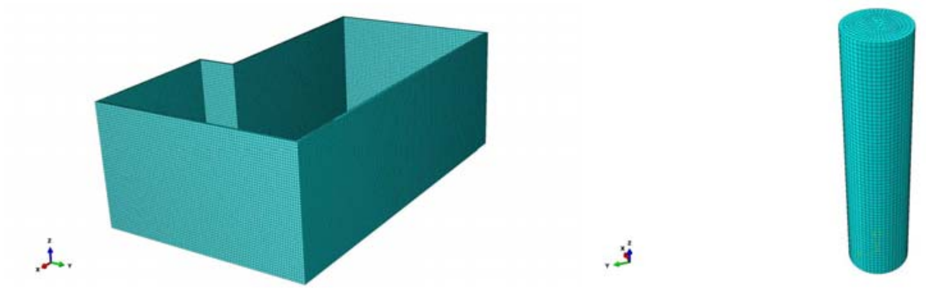

Figure 8. Analysis model of wall and bolt

The bolts and walls are both modeled as elasto-plastic material. A typical steel model with isotropic hardening is used for the bolts. The material parameters of the walls are chosen in such a way that it yields equivalent inter-story displacement as the above steel frame model under three times hydrostatic pressure. By this method, the steel frame and reinforcements can be thought as smeared into the properties of wall. The material parameters used in this simulation are concluded in the following table, where the parameters for the wall have been chosen as a concrete one.

Table 5. Coefficients for inverse simulation

	Young's Modulus	Possion ratio	Yiled stress	Hardening parameter
bolt	210000Mpa	0.3	345Mpa	0.01
wall	42000Mpa	0.2		0.01

Meanwhile, the boundary condition is another critical factor in determining the Tsunami load from the bolt deformation. On one hand, in order to provide support and share loads with the bolts, the bottom surface of the walls should also be fixed to the foundation as the bolts. On the other hand, to allow the rigid displacement of the front wall caused by its breaking free from the foundation, its bottom surface should remain loose during the simulation process. Facing both these requirements, a hybrid boundary condition is adopted in this simulation, with the front wall under consideration fixed to the foundation only by the bolts while the other walls fix entirely at the bottom surface, this hybrid boundary condition is sufficient to provide the desired behavior of the front wall and its corresponding bolts. The following two figures show the deformation and von-mises stress distribution of the walls and the front-center-bolt respectively.

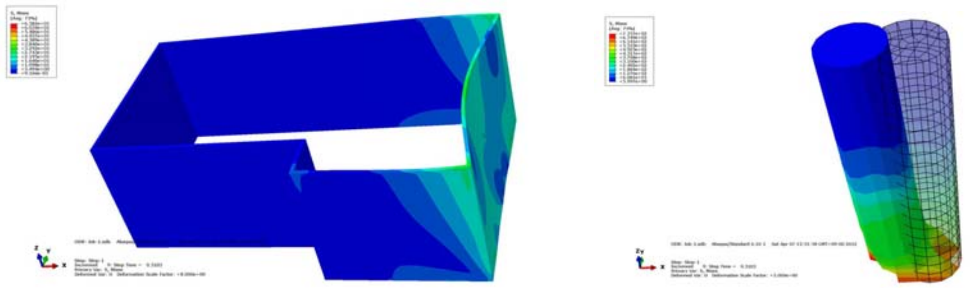

Figure 9. Stress distribution and displacement of wall and bolt

When the displacement of this bolt head reaches 14mm, the reaction force on the entire bottom surface of the model is calculated to find the tsunami force. The result is 3350KN, approximately two times the hydrostatic force of tsunami water. To confirm this result, the calculated force is further applied to the front wall and the displacement of the corresponding bolt heads are monitored and plotted against the load increments.

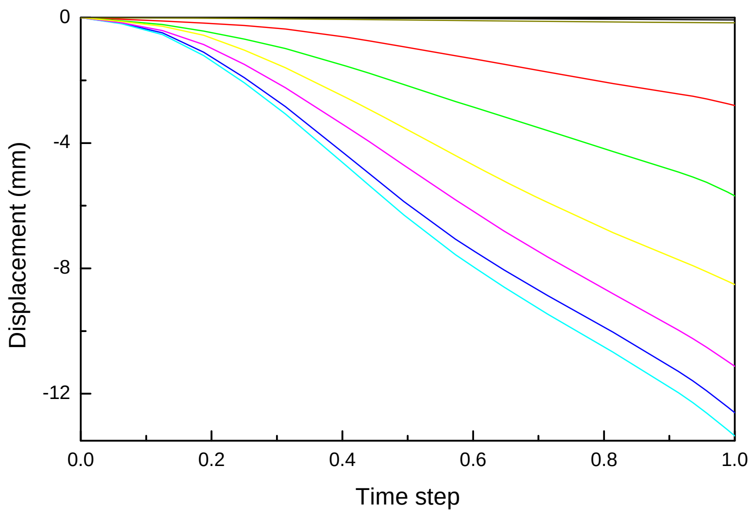

Figure 10. Displacement of bolts

In Figure 10, the displacement histories of the eight bolts belonging to the front wall are plotted, the two center bolts show the desired displacement of 14mm as observed in the field, testifies to the calculated load of 3350KN. This result shows a certain difference from the load set by design code which is equivalent to three times hydrostatic force.

5. CONCLUSION

Recent results on Tsunami load have been reported, where an independent house destroyed by the 311 Earthquake near the Arahama region has been chosen for study based on the measured data and investigation facts of this house. A scale-down model of the two-story house has been tested by shaking table experiments and wind tunnel experiments, and the results by experiments and FEM simulation including inverse calculation of Tsunami force have been compared for establishment of the Tsunami Load. Not only compared with earthquake-induced and wind-induced forces, but also compared with the Tsunami force recommended from guidance for Tsunami load in Japan, real Tsunami load shows great force in the 311 Earthquake. The results of wind tunnel experiments show the possibility that if the house was built towards different direction the Tsunami load exerted on it could be reduced significantly.

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