Response characteristics of R/C buildings considering impulsive force of tsunami drifting objects

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ABSTRACT

After the 2011 Great East Japan Earthquake, the quantitative evaluation method of tsunami load and the design guideline for tsunami evacuation buildings were established in Japan. However, the impulsive force of drifting objects such as vessels and containers etc. due to tsunami is not taken into consideration in the guideline. Therefore, it is necessary to establish the quantitative evaluation method of the impulsive force and to investigate whether the force should be taken into account to the current design guideline for tsunami evacuation buildings.

In this paper, the response characteristics of R/C buildings considering the impulsive force of tsunami drifting objects are analytically and experimentally investigated. For this purpose, nonlinear analyses are conducted to evaluate the dynamic response of a six story R/C tsunami evacuation building, and collision experiments using 1/100 scale specimens are carried out to verify the validity of analytical results.

Keywords: the 2011 Great East Japan Earthquake, tsunami evacuation building, impulsive force, drifting object, response characteristics

1. INTRODUCTION

The 2011 Great East Japan Earthquake that occurred at 14:46 local time on March 11, 2011, had magnitude of 9.0 on the Richter Scale with the epicenter approximately 70 km east of the Oshika Peninsula in Miyagi Prefecture (38.322°N, 142.369°E, Depth: 32km). This earthquake triggered terrible tsunami waves which hit the coast of Japan and propagated around the Pacific Ocean, and this tsunami caused extensive and severe building damage such as pancake collapse, overturning, movement, tilting, sliding, and debris collision. Authors conducted tsunami damage investigations in Tohoku area (from Hachinohe city in Aomori Prefecture to Soma city in Fukushima Prefecture) from the beginning of April through the end of June, 2011.

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In this paper, the response characteristics of R/C buildings considering the impulsive force of tsunami drifting objects are analytically and experimentally investigated. For this purpose, nonlinear analyses are conducted to evaluate the dynamic response of a six story R/C tsunami evacuation building, and collision experiments using 1/100 scale specimens are carried out to verify the validity of analytical results.

(a) Collapsed building due to collision (b) Large vessel drifted by tsunami

Photo 1: Building damage due to collision of tsunami drifting object

2. BUILDING RESPONSE EVALUATION BY NONLINEAR ANALYSIS

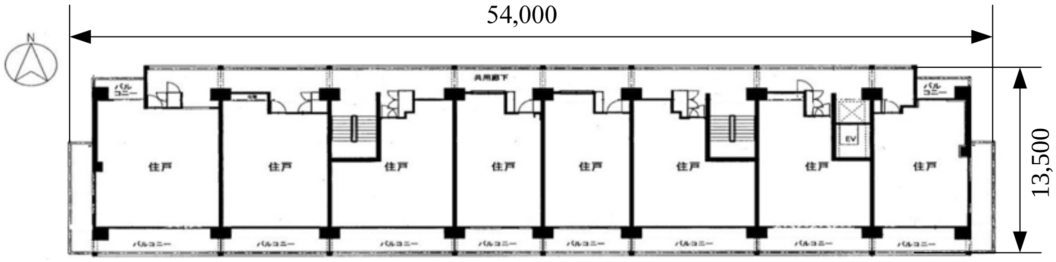
2.1 Reference building and modeling for nonlinear response analysis

In this study, a six story apartment R/C building, which is a tsunami evacuation building designed as tsunami inundation depth h=10m and water depth coefficient a=2.0 (NILIM, 2012) as shown in Figure 1, is selected to analytically evaluate the response characteristics due to both of the tsunami load and the impulsive force of a tsunami drifting object.

The assumptions on nonlinear response analyses are as follows.

(1) The reference building is replaced as six degree of freedom model with single degree of freedom per one story as shown in Figure 2.
(2) The base shear coefficient C of this building is 1.15.

(3) The hysteretic characteristic of each story is employed Takeda model (Takeda, T. et al., 1970) having yielding drift angle of 1/200 rad. and stiffness degradation factor α of 0.4 after yielding point.
(4) The well-known Newmark β method is employed for numerical integration.
(5) The predominant period of this building is set as 0.26 second, and the weight per unit floor area is assumed as 14 N/mm^2.



(a) Floor plan of first floor

(b) Elevation of sea side

Figure 1: Reference building

2.2 Estimation of tsunami load and impulsive force

As shown in Figure 2, overall tsunami load acting on the reference building is assumed a triangular shape with the height reaching the water depth coefficient *a* times of the design tsunami inundation depth *h* based on the Japanese guideline (NILIM, 2012), and the tsunami load acting on each floor is calculated by halves of story height of up-and-down story.

The debris collision force shown in Figure 2 is calculated by Mizutani equation shown in equation (1) (Mizutani, N. et al., 2007), and then the impulsive force can be computed by the product of the collision force F_m and the collision time d_t.

$$F_m = 2\rho\eta B_c V_x^2 + \frac{WV_x}{gd_t} \tag{1}$$

$$a = \sqrt{2}F_r \tag{2}$$

$$F_r = \frac{V}{\sqrt{gh}} \tag{3}$$

where,

F_m : Debris collision force (kN)

ρ : Mass per unit volume of water (1.0 t/m^3)

η : Tsunami run-up height (m, assumed as tsunami inundation height h (=9m) herein)

B_c : Width of tsunami drifting object (m)

V_x : Collision velocity (6.6 m/s, assumed as a half of tsunami flow velocity V (13.2 m/s) mentioned later)

W : Weight of tsunami drifting object (kN)

g : Gravity acceleration (9.8 m/s^2)

d_t : Collision time (s, assumed 10ms to 50ms (Mizutani, N. et al., 2007))

a : Water depth coefficient (=2.0 herein)

F_r : Froude number

V : Tsunami flow velocity (13.2 m/s, calculated by equation (2) and (3))

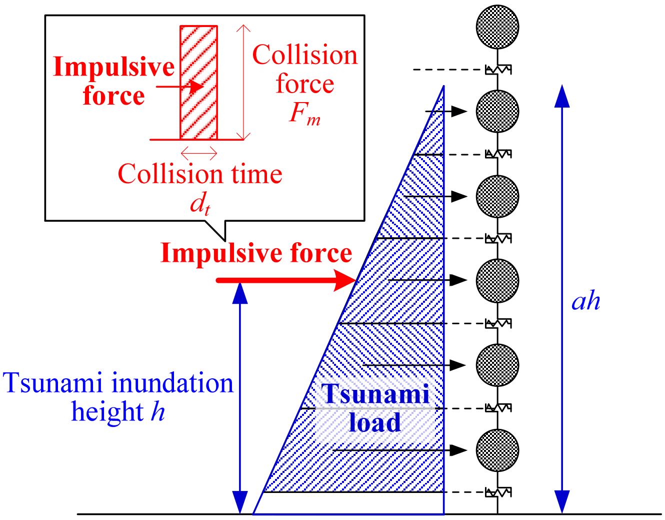


Figure 2: Schematic illustrations of tsunami load and impulsive force

2.3 Analysis parameters

Table 1 shows the parameters of this analysis. As shown in the Table, main parameter of Case 1 is the debris mass, and that of Case 2 is the collision time, respectively.

Table 1: Parameters of this analysis

	Debris mass (*t*)	**Collision time (s)**	**Collision velocity (*m*/*s*)**
Case 1	100	30	6.6
	200		
	300		
	400		
Case 2	200	10	6.6
		30	
		50	

2.4 Analysis results

2.4.1 Results of Case 1

Figure 3 shows the distribution of the ductility factor of each story according to increasing the mass of tsunami drifting objects. When only tsunami load is considered, the ductility factors of all stories are less than 1.0 of ductility factor. However, as the debris mass increases, the ductility factors of each story also increase, and yielding point is exceeded in more than 200t of the debris mass. This result means that it is occasionally necessary to take into account the influence of the collision of tsunami drifting objects at the time of the structural design of a tsunami evacuation building.

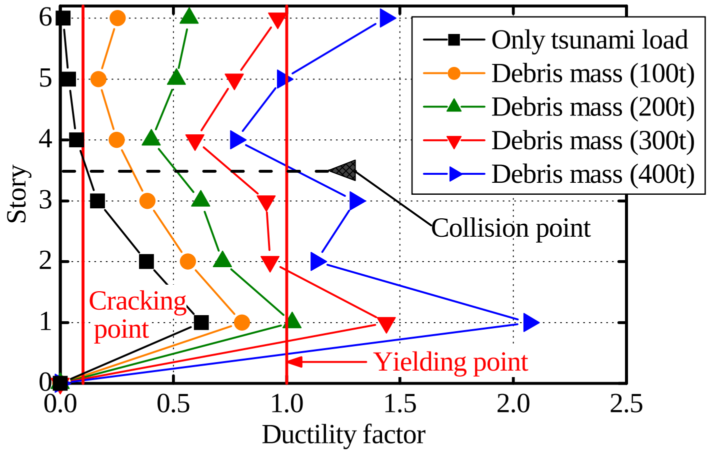


Figure 3: Ductility factor of each story according to increasing of debris mass

2.4.2 Results of Case 2

Figure 4 shows the distribution of the ductility factor of each story in accordance with changing the collision time. As shown in the figure, even if the collision time is changed, maximum ductility factors are almost the same. This result is caused by equation (1) employed in this analysis. Since the equation governs the second term, it can be briefly rewritten as equation (4). If the products of the debris mass m and the collision velocity V_x (i.e., the momentum) are the same as this case, the

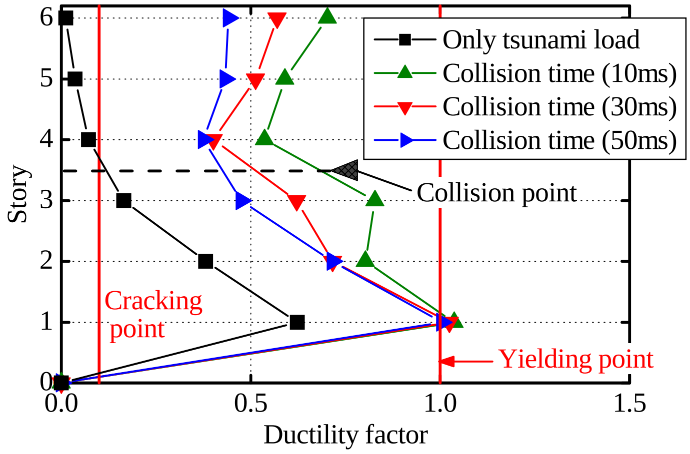


Figure 4: Ductility factor of each story according to changing collision time

collision time d_t and the collision force F_m serve as reciprocal relations as shown in equation (4). Therefore, the impulsive forces calculated by the product of the collision force and the collision time become the same, and eventually maximum ductility factors also become the same.

$$F_m d_t = mV_x \tag{4}$$

3. COLLISION EXPERIMENT USING SCALED MODEL

3.1 Outline of experiment and measurement system

In this study, 1/100-scale specimens which are model building designed by the reference building shown in Figure 1 and model tsunami drifting objects supposing vessels of 100 to 300 ton class are fabricated, and the collision tests are carried out to investigate the collision force and the collision time between model building and model tsunami drifting object. Figure 5 shows the schematic illustration of this experiment system. As shown in the figure, the model building fixed to linear slider run onto the model tsunami drifting object in this test.

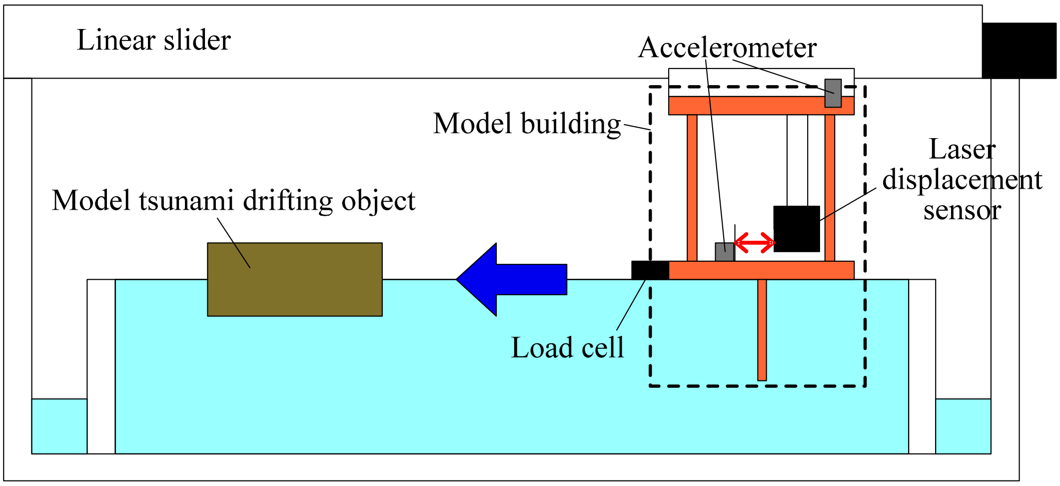


Figure 5: Schematic illustration of this experiment system

The maximum collision force F_m and the collision time d_t are calculated from the wave pattern obtained by the load cell installed the model building as shown in Figure 5. The relative lateral displacement of the model building is measured by the laser displacement sensor.

3.2 Experiment parameters

Table 2 shows the parameters of this experiment. As shown in the Table, main parameter of Case 1 is the debris mass, and that of Case 2 is the same momentum which is calculated by the product of the collision velocity and the debris mass, respectively.

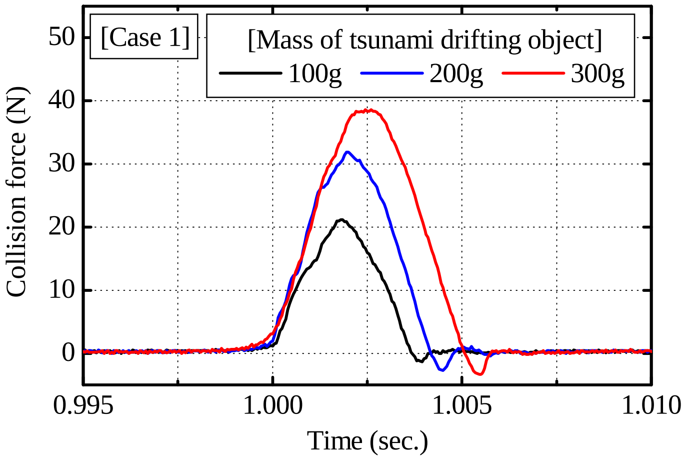
Table 2: Experiment parameters

	Collision velocity(*mm*/*s*)	**Debris mass (*g*)**	**Plate thickness (*mm*)**
Case 1	200	100	0.5
		200	
		300	
Case 2	300	100	0.5
	150	200	
	100	300	

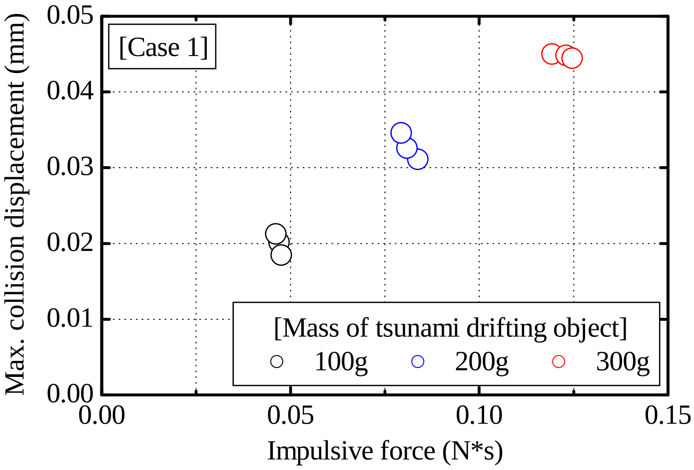
3.3 Experiment results

3.3.1 Results of Case 1

Figures 6(a) and 6(b) show the relationships between the collision force and the collision time, and the maximum collision displacement and the impulse force due to different mass of tsunami drifting object, respectively. As can be found in



(a) Relation of collision force and collision time due to mass of drifting object



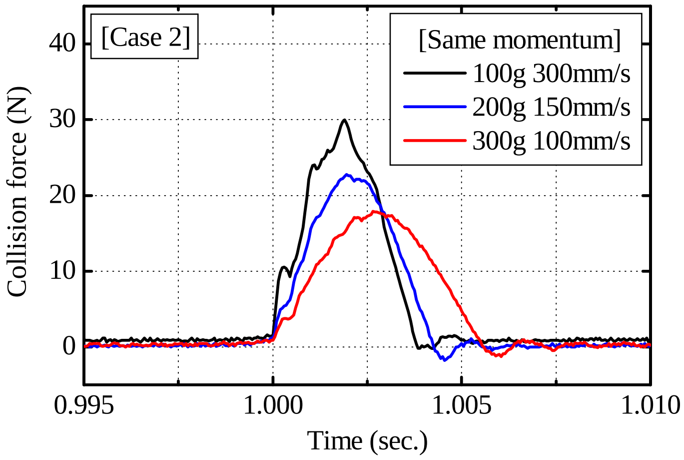
(b) Relation of collision displacement and impulsive force due to mass of drifting object

Figure 6: Results of Case 1

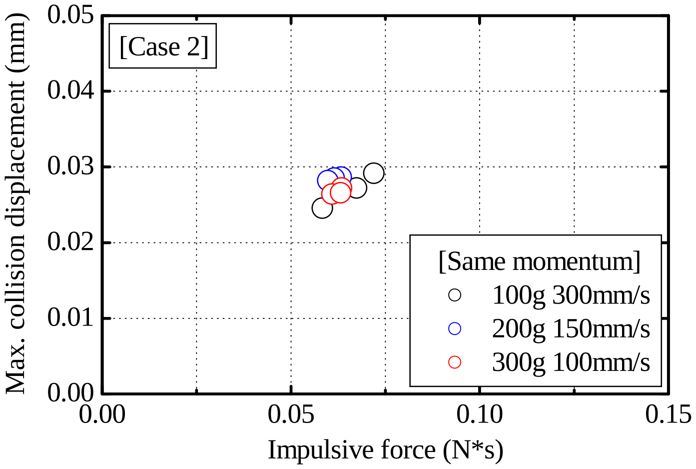
Figure 6(a), both of the collision force and the collision time quantitatively increase as the debris mass increases. Furthermore, the maximum collision displacement and impulsive force increase linearly together with increasing debris masses as shown in figure 6(b).

3.3.2 Results of Case 2

Figures 7(a) and 7(b) show the relations of the collision force and the collision time, and the maximum collision displacement and the impulsive force under same momentum, respectively. As the debris mass increases and the collision velocity decreases, the collision time increases and the collision force decreases as shown in Figure 7(a). However, the impulsive force and the collision displacement are almost the same under same momentum as shown in Figure 7(b).



(a) Relation of collision force and collision time under same momentum



(b) Relation of collision displacement and impulsive force under same momentum

Figure 7: Results of Case 2

3.3.3 Relationship between impulsive force and momentum

In this section, the relationship between the momentum of the model tsunami drifting object and the impulsive force imposed the model building is investigated.

As shown in Figure 8, the impulsive forces calculated by the product of the collision force F_m and the collision time d_t shown in equation (4) are about 2 times of the momentums obtained by the product of the debris mass m and the collision velocity V_x. This result is different from the analysis result that the impulsive force is almost equal to the momentum as shown in equation (4) and Figure 4 in section 2.4.2. This can be explained from equation (7) obtained by equations (5) and (6) based on the law of conservation of momentum and the law of conservation of energy, respectively. As shown in equation (7), the velocity v_x' of tsunami drifting object after the collision is 2 times of the velocity V_x of building before the collision when the value of α is close to zero ($M \gg m$), while v_x' is almost equal to V_x when α is 1.0 ($M=m$). In this test, since the mass of the building is quite larger than that of tsunami drifting object, the impulsive force became twice the momentum as mentioned above.

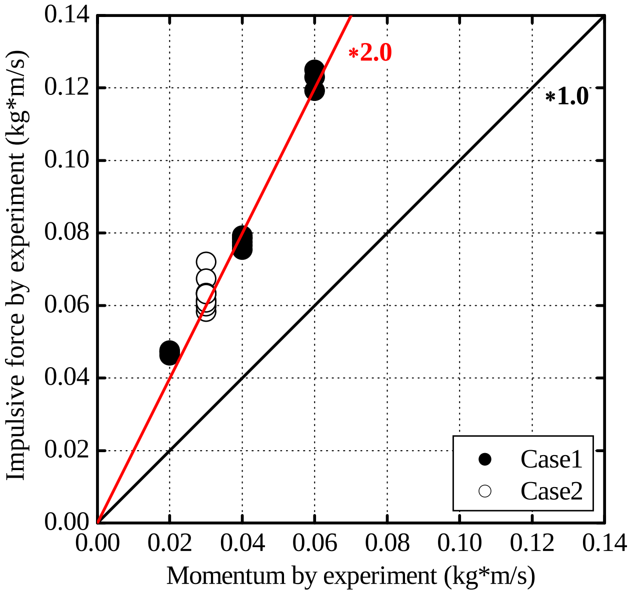


Figure 8: Relation of impulse force and momentum by experiment

$$MV_x + mv_x = MV_x{}' + mv_x{}' \tag{5}$$

$$\frac{1}{2}MV_x{}^2 + \frac{1}{2}mv_x{}^2 = \frac{1}{2}M\left(V_x{}'\right)^2 + \frac{1}{2}m\left(v_x{}'\right)^2 \tag{6}$$

$$v_x{}' = \frac{2}{1+\alpha}V_x \quad \left(\alpha = \frac{m}{M}\right) \tag{7}$$

where,

M, m : Mass of building and tsunami drifting object, respectively

V_x, v_x : Velocity of building and tsunami drifting object before collision, respectively (v is zero in this test)

V_x', v_x' : Velocity of building and tsunami drifting object after collision, respectively

α : Ratio of mass of tsunami drifting object to mass of building

4. CONCLUSIONS

In order to investigate the response characteristics of R/C buildings due to collision force of tsunami drifting objects, nonlinear response analyses and simple collision tests are carried out. The major findings can be summarized as follows.

(1) As increasing of the mass of tsunami drifting object, both of the impulsive force and the maximum displacement of the building increased in both of the analyses and the tests.

(2) When the amount of the momentum is constant, the impulsive force and the maximum displacement of the building are constant in both of the analyses and the tests.

(3) When the mass of the building is quite larger than that of tsunami drifting object, the impulsive force became twice the momentum.

In future research, the collision tests for the value of α which is the ratio between masses of building and tsunami drifting object will be carried out to establish the design procedure of a tsunami evacuation building considering the collision force.

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