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Simplified Response Estimation Method of Buildings due to Tsunami-Driven Ship Impact Loads

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Abstract

After the 2011 Great East Japan Earthquake, a joint team of the Institute of Industrial Science, The University of Tokyo (IIS UTokyo) and the Building Research Institute (BRI) conducted extensive damage investigations. Considering new findings learned from the investigation results, The Ministry of Land, Infrastructure, Transport and Tourism issued Interim Guidelines on the Structural Design of Tsunami Evacuation Buildings in November 2011. While massive waterborne debris such as ships can cause a critical global response of a building, impact loads due to the debris were not considered quantitatively in the guidelines. The authors, therefore, firstly defined an impact load due to a ship as a rectangular pulse based on the studies to evaluate the collision strength of a ship's bow. Since the building response characteristics are significantly affected by the impact durations, the durations are then derived and compared to the natural period of a buildings. Secondly, the elastic building responses due to the impact loads are obtained by modal analyses and their characteristics are investigated. The maximum inter-story drifts below the impact-imposed floor level are generally found during the impact and are larger than those above the impact-imposed floor level. They are then simply estimated by the combination of the equivalent static inter-story drift and the first order mode drift. Finally, the accuracy of the proposed simplified estimation is verified parametrically to the impact durations. As a result, the estimated maximum inter-story drifts are found in a good agreement with those computed by modal analyses when the impact duration is longer than a half of the natural period of the building. Considering that the impact duration due to a ship can be generally longer than the natural period of a low- to medium-rise reinforced concrete building, the obtained equation is found widely applicable to estimate the maximum inter-story drifts of buildings due to the ship impact loads.

Keywords: Impact Load, Tsunami, Tsunami Evacuation Building, Elastic Response Estimation

1. Introduction

Past damage observations after tsunami disasters show that a great amount of debris were generated by tsunamis and they were driven deep inland area. While massive debris such as ships can cause a critical global response of a building, the design method of buildings against the debris impact loads has not been discussed sufficiently, and hence the design method is not clearly specified in the structural design guidelines for tsunami evacuation buildings in Japan [1]. The authors, therefore, defined the impact loads due to ships and shipping containers and then proposed an estimation method of elastic building responses due to the defined impact loads [2]. Because ships are supposed to be massive enough to cause critical building responses, the building response characteristics due to the ship impact loads are further investigated in this paper. A simplified estimation method is then proposed based on the response characteristics. Finally, the applicability of the proposed method is verified. Note that the elastic building responses due to the ship impact loads are discussed in this paper; local damages to a building, degraded building's stiffness and hydrodynamic effects (e.g., tsunami load acting on building prior to the ship impact and additional mass effects) are neglected in this paper.

2. Impact Loads due to Ship Collisions

After the 2011 Great East Japan Earthquake, several ship collisions against buildings were recorded on tsunami videos, where ships were found to be more likely to cause a head-on collision with buildings [3]. Experimental results additionally indicate that colliding debris are decelerated by a wave reflected on the surface of a building, and the colliding velocity decreases more significantly as the debris width perpendicular to their traveling direction becomes larger [4]. Colliding ships traveling in parallel to the tsunami flow are therefore expected to cause the largest impact on the building, and hence they are considered in this paper to provide a safer side evaluation of the building responses.

After the head-on collision, local failures were often found only at ships' bows whereas minor damage in other parts [5]. Impact loads due to ships are, therefore, defined based on the collision strength of their bow. The bow strength P_{cr} (tf) of a steel ship was formulated considering the buckling strength of ship-hull plate, and it was examined by the static loading tests [6]. The strength P_{cr} was then expressed as a function of the gross tonnage of a ship T_G (ton) as Eq. (1), considering the statistical relationship between T_G and the thickness of the hull plate [7]. Because the strength P_{cr} was reported approximately constant regardless to the indentation of the ship's bow (i.e., buckling deformation) [6], an impact load due to a ship is defined as a rectangular pulse with a constant force F (kN) equal to P_{cr} (Eq. (2)) as shown in Fig. 1. The impact duration τ (s) is then defined as Eq. (3) assuming that the momentum of a colliding ship mv is entirely transferred to a building (i.e., the ship is assumed to stop completely after the collision).

$$P_{cr} = 1.17 T_G^{\ 1/3} \left(0.82 T_G^{\ 1/6} + 1\right)^3 \tag{1}$$

$$F = P_{cr} g \tag{2}$$

$$\tau = mv / F \tag{3}$$

where P_{cr} (tf) is the strength of a ship's bow [7]; m (t) is the mass of a ship; v (m/s) is the colliding velocity of a ship (v is assumed to correspond to the flow velocity [3]); and g (m/s^2) is the gravity acceleration.

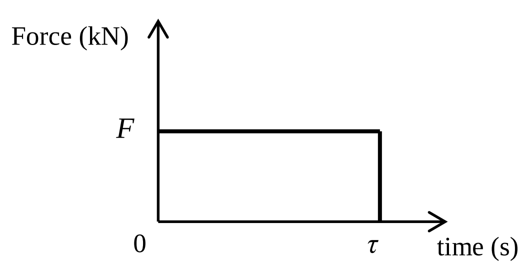

Fig. 1 – Defined time history of impact load

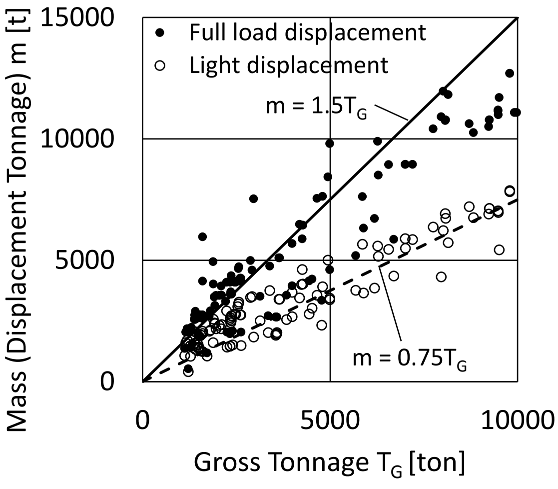

Fig. 2 – Mass versus Gross Tonnage of ship

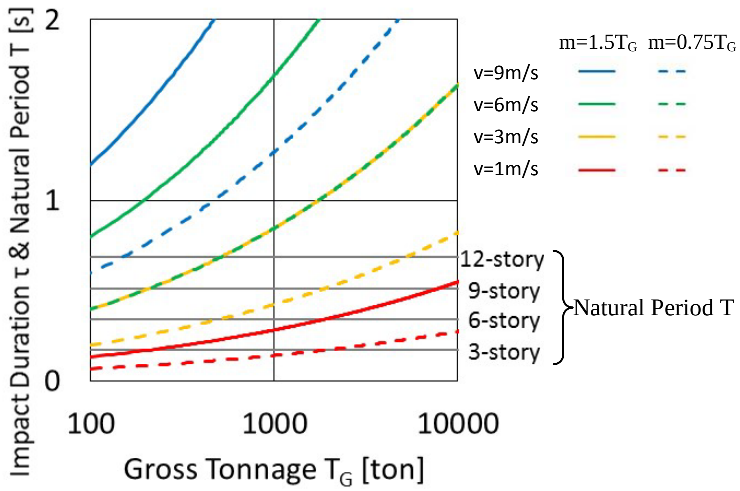

Fig. 3 – Impact duration versus Gross Tonnage of ship

Because the building response characteristics are significantly affected by the impact durations τ, the durations τ are computed by Eq. (3) and compared with the natural period of buildings T herein. Two cases of mass of a ship m (i.e., displacement tonnage) is considered in computing τ by Eq. (3): one is the light displacement and the other is the full load displacement, which averagely correspond to 0.75 and 1.5 times of Gross Tonnage of ship T_G, respectively, according to the Japanese registry ship data [8] as shown in Fig. 2. The impact durations τ are then computed by Eq. (3), assuming m=0.75T_G or 1.5T_G, and compared with the natural period of buildings T in Fig. 3. The natural period T of three to twelve story buildings are computed by the equation of T =0.02H, which is often applied to the Japanese reinforced concrete buildings (H (m) is a building height), and are shown in the figure, assuming that every story height of the buildings H is 2.85m. Note that ships exceeding 100 Gross Tonnage are considered in Fig. 3, since they are generally to be constructed of steel, and therefore Eqs. (1) to (3) can be applied to compute the impact loads due to them. The figure shows that the impact duration τ becomes longer as the Gross Tonnage T_G or the colliding velocity of a ship v increases. Considering that the flow velocities recorded in the tsunami videos after the 2011 Great East Japan Earthquake were 3m/s to 6m/s [9], τ can be generally longer than the natural period of the building T as far as low- to medium-rise buildings (i.e., 3 to 6 story buildings) are considered. The building responses due to the ship impact loads defined herein are investigated in the following chapter.

3. Elastic Response Characteristics due to Ship Impact Loads

3.1 Building Response Computed by Modal Analysis

Modal analyses are firstly made to compute the responses of a multi-mass shear system exposed to the impact loads defined in the previous chapter. The responses during the impact are firstly computed as follows. From the equation of motion expressed by Eq. (4), a displacement response vector $\{y\}$ is obtained as Eq. (5) when the i-th floor is loaded by the constant force F (kN). Here, the damping is considered proportional to the stiffness.

$$[M]\{\ddot{y}\}+[C]\{\dot{y}\}+[K]\{y\}=\{f(t)\} \tag{4}$$

$$\{y\}=\sum_{s=1}^{N}{}_su_i\{{}_su\}\frac{F}{{}_sK}\left\{1-e^{-{}_sh_s\omega t}\left(\cos_s\omega' t+{}_sh\frac{{}_s\omega}{{}_s\omega'}\sin_s\omega' t\right)\right\} \tag{5}$$

$${}_s\omega'=\sqrt{1-{}_sh^2}\,{}_s\omega \tag{6}$$

where $[M]$ (t), $[C]$ (kN s/m) and $[K]$ (kN/m) are mass, damping and stiffness matrixes, respectively; $\{y\}$ (m) and $\{f(t)\}$ (kN) are the displacement and force vectors; $\{{}_su\}$ is the s-th order mode vector; ${}_sK$ (kN/m), ${}_sh$ and ${}_s\omega$ (1/s) are the *s*-th order generalized stiffness, damping factor and angular frequency, respectively; and t (s) is the time. The inter-story drift of the *j*-th story is then obtained from Eq. (5) as Eq. (7).

$$y_j - y_{j-1} = \sum_{s=1}^{N} {}_s u_i \left({}_s u_j - {}_s u_{j-1} \right) \frac{F}{{}_s K} \left\{ 1 - e^{-{}_s h_s \omega t} \left(\cos_s \omega' t + {}_s h \frac{{}_s \omega}{{}_s \omega'} \sin_s \omega' t \right) \right\} \tag{7}$$

Here, a part of $\sum_{s=1}^{N} {}_s u_i \, {}_s u_j / {}_s K$ in Eq. (7) leads to an element α_{ij} of flexibility matrix $[\alpha]$ (m/kN) through Eq. (8).

$$\left[\sum_{s=1}^{N} \frac{{}_s u_i \, {}_s u_j}{{}_s K} \right] = [U][{}_s K]^{-1}[U]^T = [U]\left([U]^T[K][U]\right)^{-1}[U]^T = [K]^{-1} = [\alpha] \tag{8}$$

An element α_{ij} of $[\alpha]$ is the displacement of the *j*-th floor per unit force acted on the *i*-th floor. The inter-story drift of the *j*-th floor α_{ij}-α_{ij-1} below the *i*-th loaded floor level (i.e., $i \geq j$) is therefore obtained as $1/K_j$ (K_j (kN/m) is the story stiffness of the *j*-th story), and the inter-story drift above the loaded floor level (i.e., $i < j$) is zero because no lateral force acts above the *i*-th floor. Considering the discussion mentioned above, Eq. (9) is obtained.

$$\sum_{s=1}^{N} \frac{{}_s u_i \left({}_s u_j - {}_s u_{j-1} \right)}{{}_s K} = \alpha_{ij} - \alpha_{ij-1} = \frac{1}{K_j} \qquad (i \geq j)$$

$$= 0 \qquad (i < j) \tag{9}$$

The inter-story drift during the impact (i.e., $t \leq \tau$) is then obtained from Eqs. (7) and (9) as Eq. (10).

$$y_j - y_{j-1} = \frac{F}{K_j} - \sum_{s=1}^{N} \left({}_s u_j - {}_s u_{j-1} \right) {}_s u_i \frac{F}{{}_s K} e^{-{}_s h_s \omega t} \left(\cos_s \omega' t + {}_s h \frac{{}_s \omega}{{}_s \omega'} \sin_s \omega' t \right) \qquad (i \geq j, t \leq \tau)$$

$$= \quad - \sum_{s=1}^{N} \left({}_s u_j - {}_s u_{j-1} \right) {}_s u_i \frac{F}{{}_s K} e^{-{}_s h_s \omega t} \left(\cos_s \omega' t + {}_s h \frac{{}_s \omega}{{}_s \omega'} \sin_s \omega' t \right) \qquad (i < j, t \leq \tau) \tag{10}$$

Secondly, the responses after the impact are computed as follows. The inter-story drift of the *j*-th story after the impact y'_j - y'_{j-1} (i.e., $t > \tau$) is obtained through combining the response due to the force F expressed by Eq. (10) and the response due to the force (-F) imposed in the opposite direction.

$$y'_j - y'_{j-1} = [y_j(t) - y_{j-1}(t)] - [y_j(t-\tau) - y_{j-1}(t-\tau)] \qquad (t > \tau) \tag{11}$$

3.2 Response Characteristics due to Ship Impact Loads

The building responses due to the ship impact loads obtained above are investigated in this section. A six-degree-of-freedom model is exposed to the impact loads defined earlier, and its inter-story drifts during and after the impact are obtained from Eqs. (10) and (11), respectively, where each mass of the model is assumed equal in each floor, and the story stiffness of the model is defined so that the first-order mode profile is linear along its height.

Firstly, the maximum inter-story drifts along the building's height are shown in Fig. 4 when one single floor is loaded with the impact duration τ of 0.1${}_1T$, 0.5${}_1T$, 1.0${}_1T$ and 2.0${}_1T$ (${}_1T$ is the natural period of the model), assuming the damping factor h_1=0.02. Note that the inter-story drifts are normalized by F/K_1 in the figure. As shown in Fig. 4(c) and (d), when the impact duration τ is 1.0 ${}_1T$ and 2.0 ${}_1T$, the maximum inter-story drifts below the impact-imposed floor level are larger than those above the impact-imposed floor level. In the case of τ = 0.1 ${}_1T$ and 0.5 ${}_1T$ (Fig. 4(a) and (b)), however, the impact-imposed floor level does not create a significant difference in response unlike the cases of τ =1.0 ${}_1T$ and 2.0 ${}_1T$. Because the impact duration τ due to a ship with a velocity

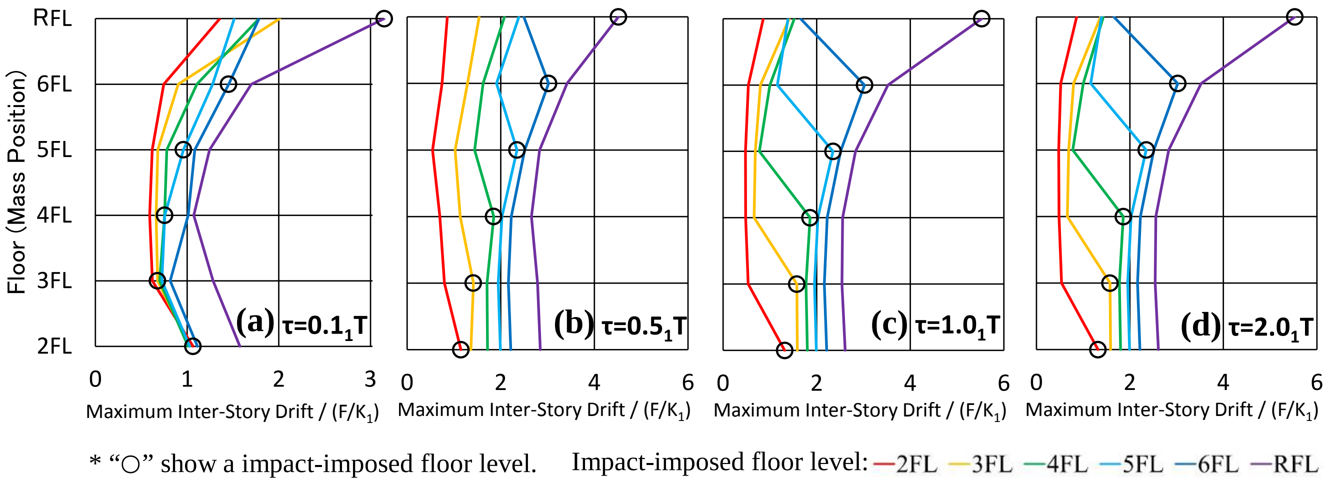

Fig. 4 – Maximum inter-story drifts along building's height

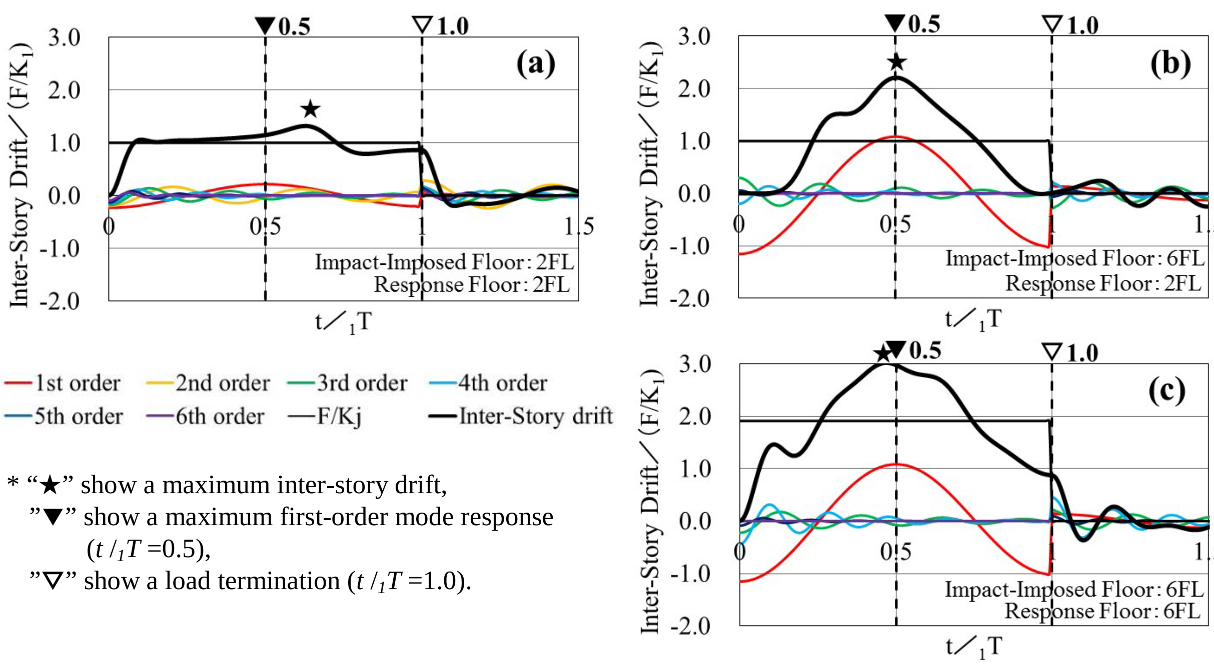

Fig. 5 – Time histories of inter-story drifts

of 3m/s to 6m/s, which corresponds to the observed flow velocity in the past tsunami event as mentioned in the previous chapter, is generally longer than the natural period ${}_1T$ of six story building as shown in Fig. 3, the inter-story drifts below the impact-imposed floor level are supposed to be critical in the structural design against the ship collisions as found in Fig 4(c) and (d). They are therefore focused in the following discussions.

Secondly, the time histories of the inter-story drifts during and after the impact are computed by Eqs. (10) and (11), respectively, and they are shown in Fig. 5. The figure shows the time histories of 2FL when 2FL is loaded and those of 2FL and 6FL when 6FL is loaded, together with their each modal responses and F/K_j in the equations. In this investigation, the impact duration τ is assumed equal to the natural period of the building ${}_1T$ in the figure (i.e., $\tau = {}_1T$); when ${}_1T$=0.34s, assuming a six-story reinforced concrete building, for example, τ is also 0.34s. Note that time t and the inter-story drifts are normalized by the natural period of the building ${}_1T$ and F/K_1, respectively, in the figure. Major findings from Fig. 5 are summarized as follows:

1. The time when an inter-story drift reaches its maximum value (★) and the time when a first-order mode response reaches its maximum value (▼, $t\,/_1T$ = 0.5) are close each other, and both of them are found during the impact (i.e., before the termination of the loading (▽, $t\,/_1T$ = 1.0)).
2. In the responses during the impact, F/K_j is predominant when 2FL is loaded (Fig. 5(a)), and F/K_j and first-order mode are equally contributing to the building's response when 6FL is loaded (Fig. 5(b) and (c)). In both cases, the maximum inter-story drifts are approximately equal to the summation of F/K_j and the first-order mode amplitude.

Considering the above findings, the combination of F/K_j and first-order mode during the impact is obtained to estimate the maximum inter-story drifts in the next chapter.

4. Simplified Response Estimation Method due to Ship Impact Loads

Based on the response characteristics below the impact-imposed floor level investigated in the previous chapter, the responses are estimated by a simplified equation and its applicability is discussed subsequently.

4.1 Elastic Response Estimation by Simplified Equation

The combination of F/K_j and the first-order mode during the impact is obtained from Eq. (10) as Eq. (12), assuming the damping factor ${}_sh$=0.

$$\delta_j = \frac{F}{K_j} + \left| \left({}_1u_j - {}_1u_{j-1} \right)_1 u_i \right| \frac{F}{{}_1K} \qquad (i \geq j) \tag{12}$$

Assuming that the first-order mode profile is linear to building's height, Eq. (12) leads to Eq. (13).

$$\delta_j = \frac{F}{K_j} + i \frac{F}{\sum_{j=1}^{N} K_j} \qquad (i \geq j) \tag{13}$$

Eq. (13) is a remarkably simple equation, by which the maximum inter-story drifts due to the impact loads can be estimated using the force F, the story stiffness K_j and the impact-imposed floor level i.

Three to twelve story building models are exposed to the impact loads to examine the accuracy of Eq. (13), where each mass is equal in each floor and the story stiffness is defined so that the first-order mode profiles are linear along their height. The maximum inter-story drifts of the model computed by modal analyses (Eq. (10)) and those estimated by Eq. (13) are compared in Fig. 6. The results are shown parametrically to the ratio $\tau/_1T$ (${}_1T$ is the first-order natural period of a model) in the figure. The figure shows that the plots lie around 1.0 and the estimated maximum inter-story drifts are found in a good agreement with the results of modal analyses when $\tau/_1T \geq 0.5$. When $\tau/_1T < 0.5$, however, they lie above 1.0 and the maximum inter-story drifts are found generally overestimated. This is because the impact load is terminated before the inter-story drift reaches its maximum value ($t\,/_1T \approx 0.5$ as found in Fig. 5) when $\tau/_1T < 0.5$.

4.2 Applicability of Proposed Method

In the previous section, Eq. (13) is found to successfully estimate the maximum inter-story drifts accurately when $\tau/_1T < 0.5$. The impact duration τ is dependent on a Gross Tonnage of a ship T_G as shown in Fig. 3, and the natural period of the building ${}_1T$ is generally dependent on its height (i.e., number of stories N). Because T_G and N are more fundamental parameter than τ and ${}_1T$ in the practical design, the applicability of the method is re-examined through T_G and N herein: the relationship between T_G and N for $\tau/_1T$ = 0.5 is investigated. As was done earlier in this study, the mass m of a ship is assumed 0.75 or 1.5 times of the Gross Tonnage of a ship T_G in computing τ by Eq. (3), and the natural period of a building ${}_1T$ is computed by ${}_1T$ =0.02H, assuming every story height is 2.85m. The minimum Gross Tonnage of a ship T_G to satisfy the $\tau/_1T$ = 0.5 is then computed and shown in Fig. 7. When T_G is larger than the plots in the figure (i.e., $\tau/_1T \geq 0.5$), the maximum inter-story drifts can be

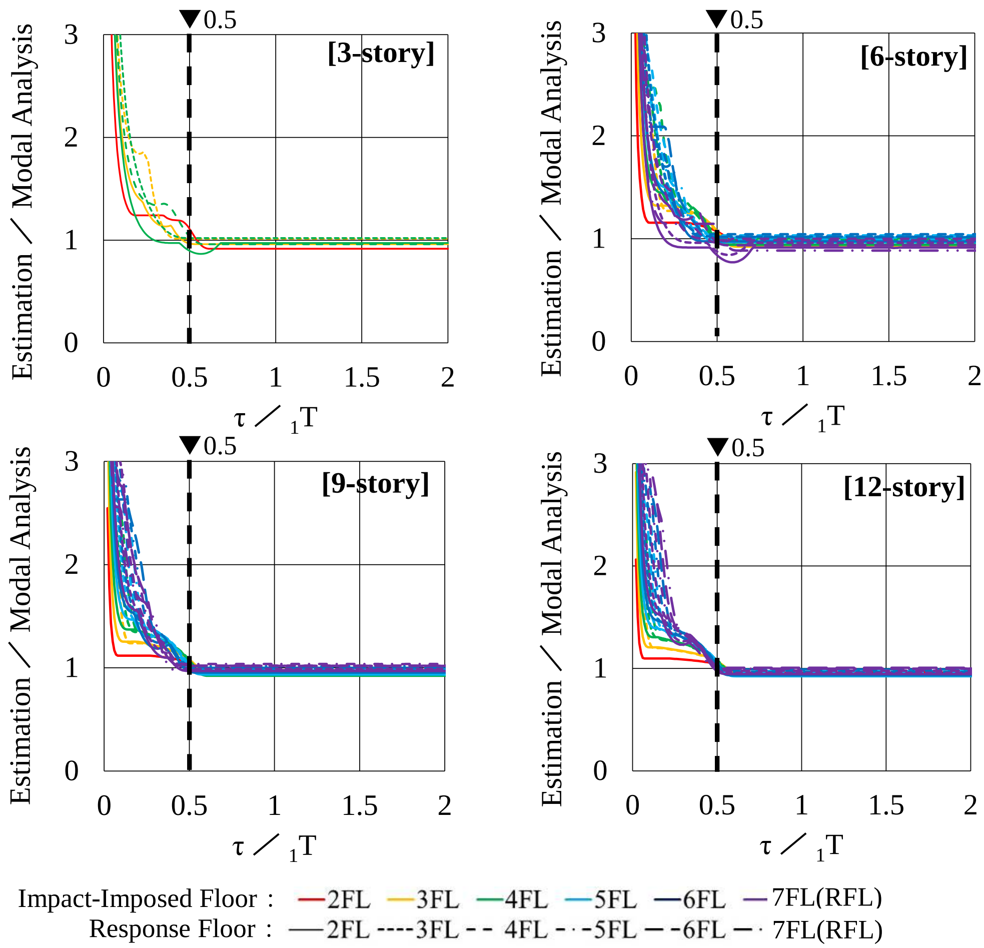

Fig. 6 – Comparison between estimation by Eq. (13) and modal analysis by Eq. (10)

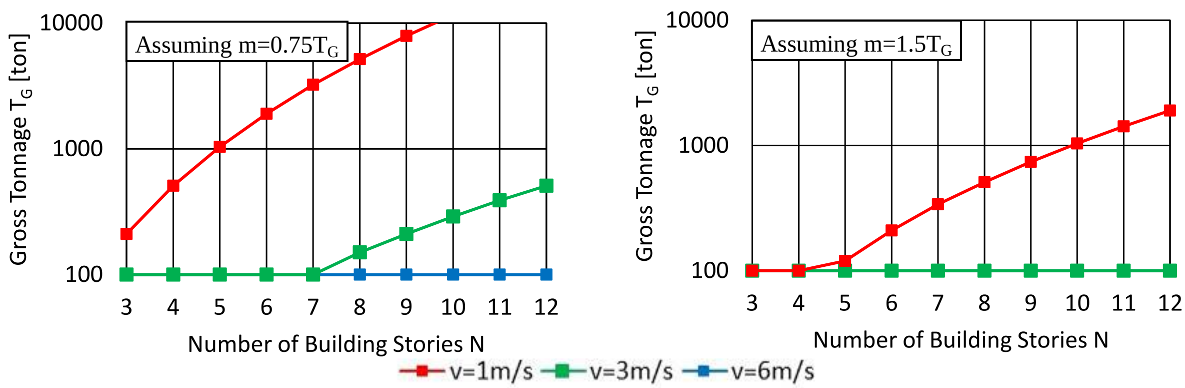

Fig. 7 –Minimum Gross Tonnage of ships to safisfy $\tau/{}_1T$ =0.5 for succesful response estimation by Eq. (13)

accurately estimated by Eq. (13). Considering that the flow velocities after the 2011 Great East Japan Earthquake varied from 3 to 6 m/s [9] as mentioned in the previous chapter, Eq. (13) can be found widely applicable to estimate the maximum inter-story drifts of the low- to medium-rise buildings due to the ship impact loads as shown in Fig. 7. It should be noted, however, that the maximum inter-story drifts can be overestimated when a building is collided by a ship of smaller tonnage with lower velocity such as 1m/s.

5. Conclusions

To propose an estimation method of a building response due to a ship impact load, the impact load is firstly defined, and the building responses due to the defined loads are obtained by modal analyses. Based on the building response characteristics, the maximum responses are estimated by a simplified equation and its applicability is examined. The major findings can be summarized as follows:

1. An impact load due to a ship is defined as a rectangular pulse, referring to the previous studies to evaluate the strength of a ship's bow. Although the defined impact duration depends on the Gross Tonnage and the colliding velocity of a ship, it can be generally longer than the natural period of a low- to medium-rise reinforced concrete building.
2. The maximum inter-story drifts below the impact-imposed floor level are generally found during the impact and are larger than those above the impact-imposed floor level. They are then found simply estimated by the combination of the equivalent static inter-story drift and the first order mode drift (Eq. (13)).
3. The maximum inter-story drifts estimated by Eq. (13) are found in a good agreement with the results of modal analyses when the impact duration τ is longer than $0.5{}_1T$ (${}_1T$ is the natural period of a building). Considering that the impact duration due to a ship can be generally longer than the natural period of a building, Eq. (13) is found widely applicable to estimate the maximum inter-story drifts due to the ship impact loads.

The simplified method proposed in this paper will be further examined to estimate the inelastic responses under hydrodynamic effects.

6. Acknowledgements

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