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ANALYTICAL STUDY ON THE COLLISION LOAD DISTRIBUTION BETWEEN A LARGE VESSEL AND A CABLE STAYED BRIDGE TOWER DUE TO TSUNAMI

J. H. Choi [(1)], T. Nagahara[(2)], Y. Kajita[(3)]

[(1)] *Assistant Professor, Kyushu University, choi@doc.kyushu-u.ac.jp*
[(2)] *Graduate Student, Kyushu University, nagahara@doc.kyushu-u.ac.jp*
[(3)] *Associate Professor, Kyushu University, ykajita@doc.kyushu-u.ac.jp*

Abstract

By the tsunami on 11 March 2011, many vessels drifted and they caused not a few damages on bridge structures such as the collision between a vessel and a pier or a superstructure. In order to design tsunami resisting structures, it is required to clarify the influence of the collision force on the bridge structure. In this study, in order to clarify the collision load distribution when a large vessel drifted by tsunami collides with bridge structures, collision analyses using FEM were conducted. Here in, it was presupposed that the drifted large vessel would collide with a tower of a long span cable stayed bridge with 1000 m length. Taking account of various collision conditions, the parametric analyses which were varied with collision positions and collision directions carried out. It was found that the collision load when the vessel collided with the lower part of the tower was larger than it when the vessel collided with upper part of the tower. And the collision load when the vessel collided in a vertical direction was smaller than it when the vessel collided in horizontal direction. Additionally, we compared the value of a collision load formula based on a log normal distribution and it calculated from the FE analytical result. From the result, the maximum collision load of FE result was a little larger than it of the formula due to the difference in the vessel behavior evaluation after the collision.

Keywords: Tsunami; Drifting Vessel; Cable Stayed Bridge Tower; Collision Load Distribution

1. Introduction

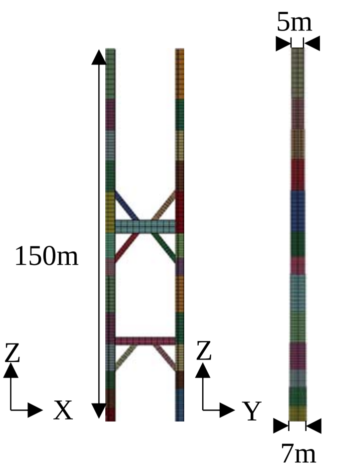
In 2011 off the pacific coast of Tohoku Earthquake, enormous damages by a plurality of tsunami occurred. In the damages, many vessels drifted and collided with a structure and multiplex damages such as a large fire spread caused. No fatal damage in bridge as like a collapse of pier and a fall of superstructure structure by the collisions of tsunami drifts was reported [1]. However, the damaged bridges by ground shaking could be easily damaged by the collision of huge drifts as like vessel by tsunami surged after great shake. Therefore, it needs to take account of the damage which could be caused by a huge tsunami when designing a bridge structure. However there are few studies on the design method of the bridge structure for tsunami. In a few previous studies of design load for tsunami, though the collision load distribution has been evaluated the formula from a log normal distribution, it has not been verified by any experiments or analyses.

In this study, in order to clarify the collision load distribution when the vessel drifted by tsunami collides with bridge structures, collision analyses of a large vessel and a long span cable stayed bridge tower using FEM were conducted. Taking account of various collision conditions, the parametric analyses which were varied with collision position and direction carried out. In addition, the collision load distribution calculated from the FE analyses was compared with it obtained from a log normal formula.

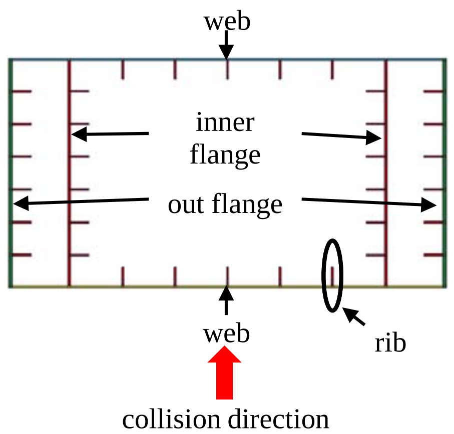
2. Analytical model and conditions

2.1 Bridge tower model

In this study, a tower of a virtual cable stayed bridge with 1000 m length was used in the FE analyses. Fig.1 shows the analytical model of bridge tower and the cross-section of tower. For high precision evaluation of collision load and deformation of elements collided by a drifted vessel, the analytical models were modelled using solid elements. The height of tower was 150m and the widths of a web plate were changed with 7 m ~ 5 m from the bottom to the top. The tower section consisted of out flange, web plate, inner flange and rib. The nonlinear material model of the bridge tower based on steel material model with isotropy elastoplastic body model was used. Table.1 shows the material characteristics of SM570 which were used in the bridge tower members. Stress-strain curve of it was shown in Fig.2 (a). In decision of the elements sizes of the tower, the analyses which were varied with the elements sizes were previously conducted in order to evaluate the collision load distribution and deformation of members precisely. The collision load distribution could be changed by the element size of the member which the vessel collided and deformable member as like the inner flange as shown in Fig.1 (b). Accordingly, the element sizes of the web which the vessel collided and inner flange models was



(a) Bridge model

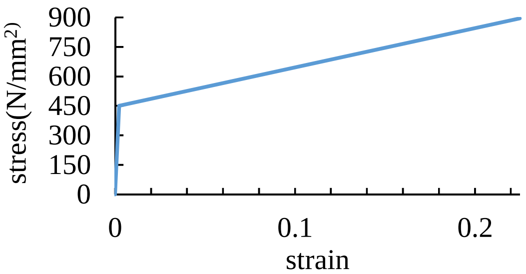


(b) Cross section of tower model

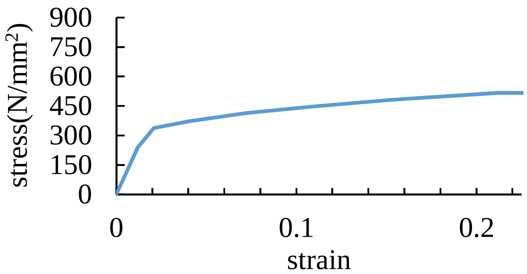
Fig. 1 – Analytical model of bridge tower

Table 1 – Material characteristics

	SS400	SM570
Density (kg/m^3)	7850	7850
Young's Modulus (GPa)	200	200
Poisson's Ratio	0.3	0.3
Yield Stress(N/mm^2)	450	320



(a) SM570



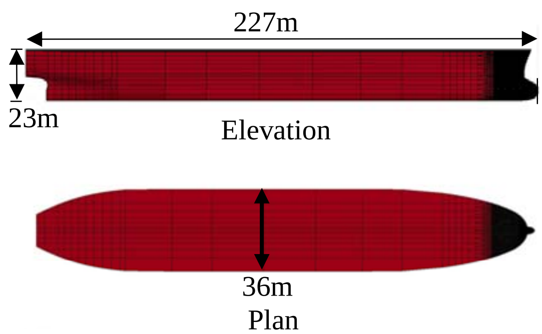
(b) SS400

Fig. 2 – Stress-strain curve

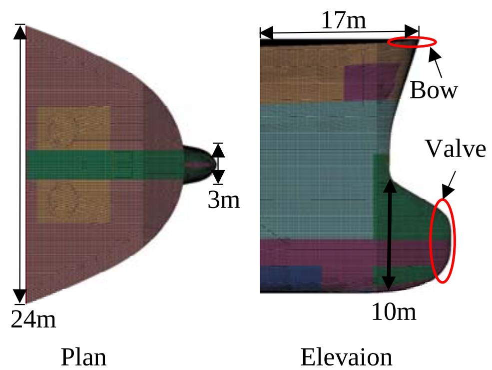
used with rectangular parallelepiped of 40×100×80 mm (X direction×Y direction×Z direction). The other elements sizes were modelled by rectangular parallelepiped of 40×600×500 mm.

2.2 Vessel model

In this study, a real size vessel model which was widely used as LNG tank vessel was used. The vessel models with total mass 15000 t, length 227 m, width 36 m and height 23 m were used in the analyses. The analytical model of vessel used in this study was shown in Fig.3. The vessel models were composed of shell elements. The material of the front part of the vessel was SS400 and Table 1 shows the material characteristics. Stress-strain curve of SS400 was shown in Fig.2 (b). The nonlinear material model of vessel with isotropy elastoplastic body model which was same model as bridge tower model was used. The element sizes of the front parts of vessel model which collided with the tower were about 120 mm in order to evaluate deformation precisely. On the other hand, rigid elements were used because of less impact on the rear part of the vessel model.



(a) Vessel model



(b) Front part

Fig. 3 – Analytical model of vessel

2.3 Analytical conditions

In all the node of the bottom of the tower, all degree of freedom were fixed as a boundary condition. The sectional elements were completely connected in the parts where the cross sections were changed.

The collision loads in the analyses were calculated by the penalty function method which consists of the interface virtual spring elements between contact surfaces [2]. When the transformation of the spring elements occurred, collision load was calculated by the equation (1).

$$f = \frac{f_{si} K A^2}{\mathrm{V}} \Delta u n \tag{1}$$

Where f is collision load, f_{si} is penalty coefficient (=1.0), K is modulus of elasticity of volume, A is contact surface area, V is contact element volume, Δu is penetration of contact surface and n is normal vector of contact surface.

The damping of the collision surface between the vessel and the bridge tower was not considered in this study because the influence of the damping on a collision load was not high in a preliminary inspection. The friction force on collision surface was not considered in the analyses because it is unknown that how much of the friction force would be generated in a collision.

It is assumed that the vessel drifted was uncontrolled by tsunami and drifted at velocity of 0.6 m/s. Though many drifts were drifted at high speed in 2011 off the pacific coast of Tohoku Earthquake, the reason we used the low drift speed of 0.6 m/s in this study was because of evaluating the collision force in elastic behavior range. Besides, assuming that the vessel floated underwater, gravitation was not considered in the analyses. In this study, LS-DYNA (Ver.971) widely being used in collision analyses was used.

3. Collision analyses of a vessel model and a bridge tower model

3.1 A parametric study on collision load distribution changing collision position

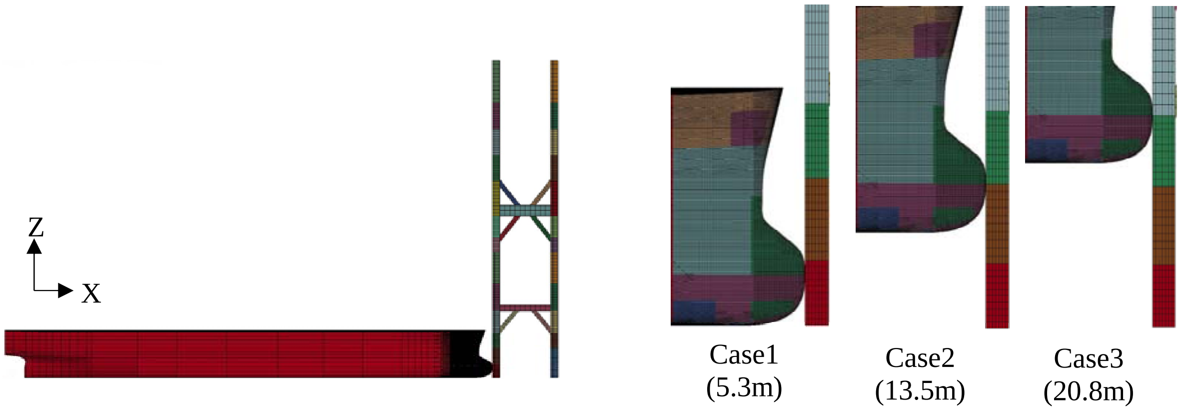
Japan Meteorological Agency observed very high tsunami height in the 2011 off the pacific coast of Tohoku Earthquake [3]. For example, the tsunami height was more than 9.3 m in Soma and Fukusima and it was more than 8.6 m in Ayukawa, Ishinomaki-shi and Miyagi in northeast Japan. From above the past observation of tsunami height, the vessel drifted by a tsunami could be collided at various positions of structure. Here in, the collision analyses as a parameter by collision position on the tower model were carried out.

3.1.1 Analytical case

In this study, three cases collision analyses which were varied with collision position of the bridge tower were conducted. The heights which the vessel collides with the tower were 5.3 m in Case1, 13.5 m in Case2 and 20.8 m in Case3, respectively. The Fig. 4 shows the analytical model of Case1 and collision positions of each case. Case1 was the case that the vessel collided at the same height of the base of the tower. Case2 was the case that the vessel collided at the position which was higher than the base of the tower in order to investigate the influence of the boundary condition near the collision section of tower. Case3 was the case that the height was 7.3m higher than Case2 to investigate the influence of the cross section of the tower.

3.1.2 Analytical result

Fig. 5 shows collision load distribution in Case1 and Case2, the comparison of the displacements of the web plates on the position with which the vessel collided. The deflection of the tower was included in the displacements, however it was verified that the deflection of the tower by the collision hardly occurred. The maximum collision loads of Case1 and Case2 were 14920 kN and 12719 kN, respectively. From the results, collision force in Case1 was 2201 kN larger than it in Case2. In order to investigate the reason for the different result, in this study, the deformations of the tower were focused on. The Fig. 5 (b) shows the deformation of the

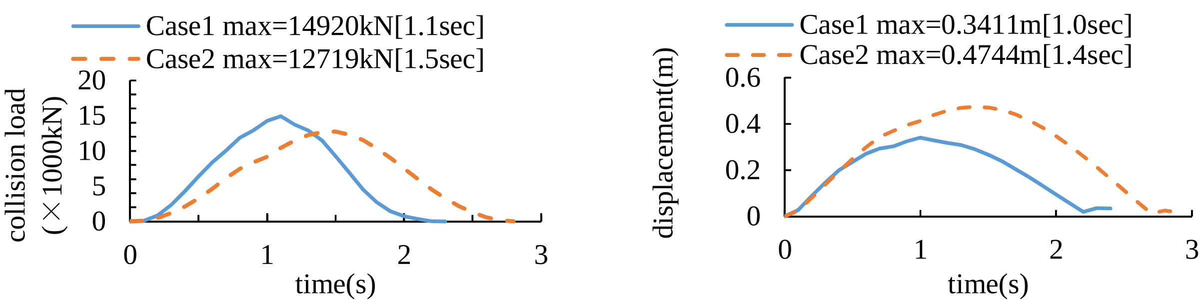


(a) Collision model (Case1) (b) Collision position on the tower model

Fig. 4 – Analytical case for collision position

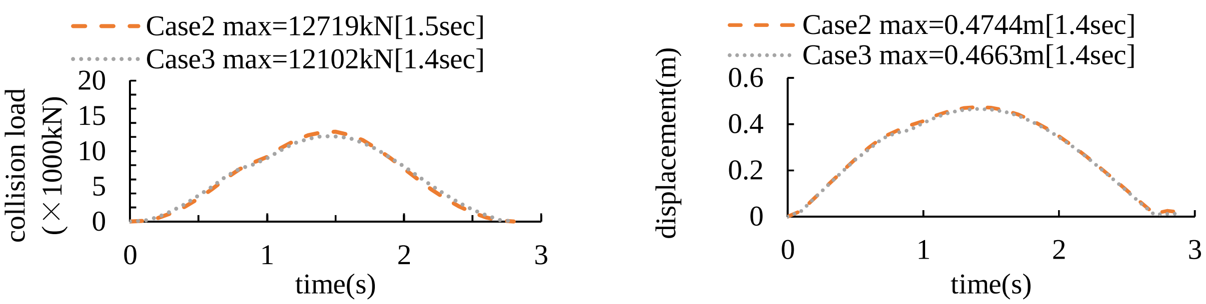
tower in Case1 more greatly than it in Case2. It was considered that the tower was difficult to deform in the case that the vessel collided with the position near the base of the tower because the nodes of the base were fixed in the analytical model. Therefore, it was found that the collision energy from the vessel was hard to act on the transformation of the tower section and the collision load became larger in the collision position near the base of the tower.

Fig. 6 shows the comparison of collision load distributions and the displacements of the web plate on the position that the vessel collides in Case2 and Case3. Fig. 6 (a) shows that maximum collision loads in Case2 and Case 3 were 12719 kN and 12102 kN. The collision loads and the displacements of both cases were close. Consequently, the influence of the cross section of the tower on the collision load distribution was not high.



(a) Collision load distribution (b) Displacement of tower

Fig. 5 – Comparison of Case1 and Case2



(a) Collision load distribution (b) Displacement of tower

Fig. 6 – Comparison of Case2 and Case3

In summary, collision load distribution noticeably depends on the transformation of the tower by the vessel collision. It is important to consider the transformation of the tower by collision in design tsunami resisting structures.

3.2 A study on the changes of collision load distributions by the difference of collision direction

There is a possibility that the vessel drifted by tsunami collides with bridge structures in various situation and it needs to consider such situation in order to design tsunami resisting structures. Here in, the collision analyses varied with collision directions were carried out.

3.2.1 Analytical case

Here in, 5 cases collision analyses (including Case1 above mentioned) were carried out. Fig. 7 shows the model of each analytical case. In the figure, yellow line shows X direction and red arrow shows collision direction. In addition, a small red arrow shows the slope of the vessel and a large red arrow shows collision direction in Case7. At first, Case4 and Case5 show the analytical models from Y direction. The vessel inclined to the top at ten degrees for the tower collides with the tower from the direction in Case4. Additionally, the vessel inclined to the under at ten degrees for the tower collides with the tower from the direction in Case5.

Case6 and Case7 show the analytical models from Z direction. The vessel inclined to Y direction at ten degrees for the tower collides with the tower from the direction in Case6. On the other hand, in Case 7, though the vessel was inclined like as Case6, the vessel collides with the tower from X direction.

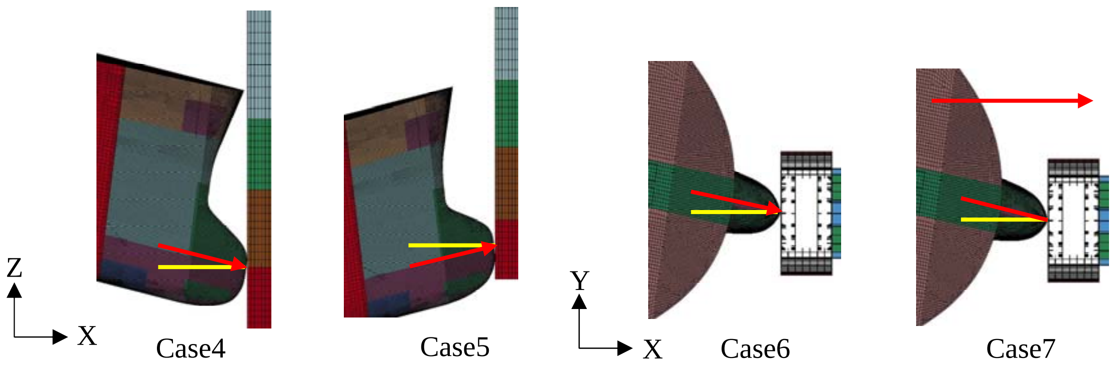


Fig. 7 – Analytical model for collision direction

3.2.2 Analytical result

Fig. 8 shows collision load distributions in Case1, Case4 and Case5. Fig. 9 shows the displacements of the web plate of the tower that the vessel collides in X direction and Z direction in Case4 and Case5, respectively. Fig. 10 shows the comparison of the deformation of the valve part in the vessel. Fig. 11 shows the aspect of the collision when the tower section transformed

First, maximum collision load in Case4 was 1713 kN, which was smaller than that in Case1 because the plastic deformation of the bow part of the vessel due to the collision on the bow. On the other hand, maximum collision load in Case5 was 10407 kN, which was 4513 kN smaller than that in Case1. Furthermore, the maximum displacement of the tower in Case1 was larger than it in Case5 as shown in Fig. 9 (a). This result was different from it which was evaluated in the above examination. It can be also verified by Fig. 11. It could mean that not only the tower but also the vessel could be deformed by the collision. The deformation of the valve part of the vessel in Case5 was bigger than one in Case1 as shown in Fig. 10.

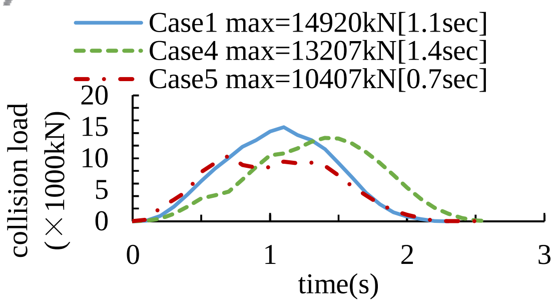


Fig. 8 – Collision load distribution

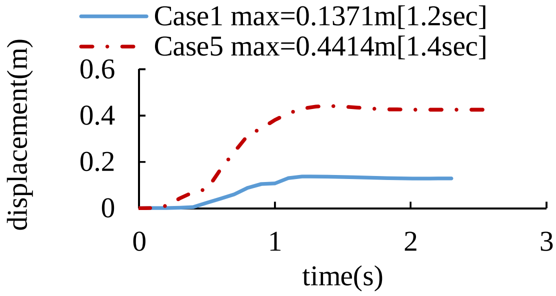
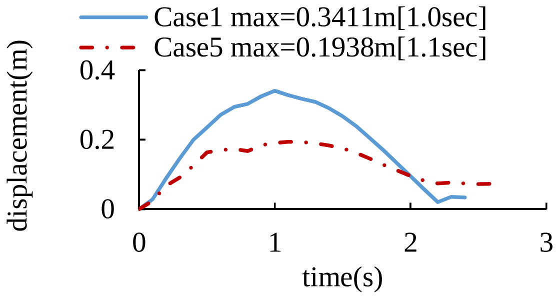
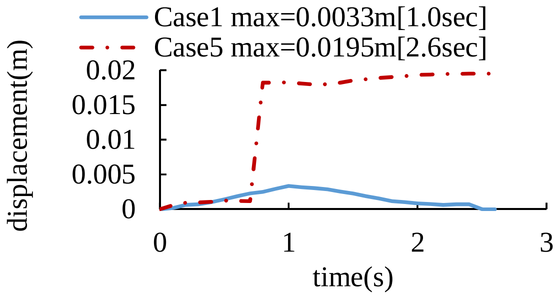


Fig. 10 – Deformation of valve

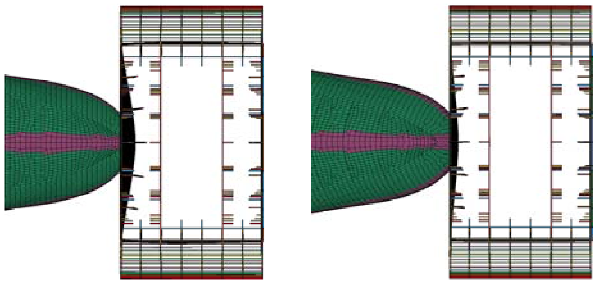


(a) X direction



(b) Z direction

Fig. 9 – Displacements of tower



Case1 Case5

Fig. 11 – Aspects of collision

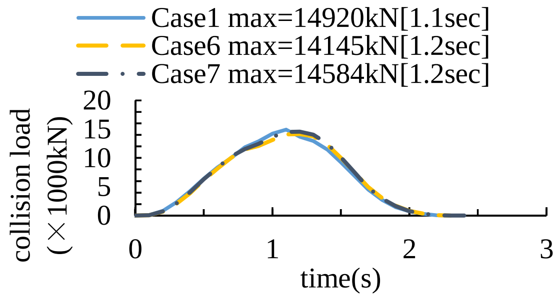


Fig. 12 – Comparison of collision load distribution

Fig. 12 shows collision load distribution in Case1, Case6 and Case7. Each of maximum collision force became close value. Consequently, the influence of direction changes in the horizontal direction on the collision load distribution was not high.

By means of above results, the collision load distribution when the vessel collides in a vertical diagonal direction could be smaller than it when the vessel collides in a horizontal diagonal direction due to the deformation of the vessel.

4. Comparison between the value of collision load formula and analytical result

4.1 An estimated collision load formula based on a log normal distribution

An estimated the collision load distribution used in this study was assumed that the vessel completely stops after the vessel collided with the tower and the lost momentum converts the collision load formula based on a log normal distribution. The collision load distribution was referred as shown in Eq. (2).

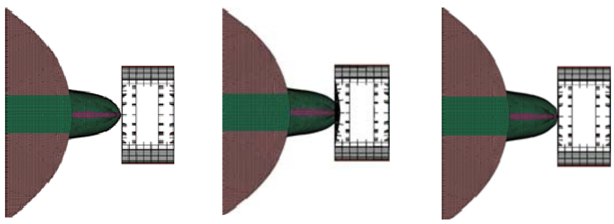
$$F(t) = \frac{mv}{\sqrt{2\pi} \cdot \sigma} \cdot e^{-\frac{(t-\mu)^2}{2\sigma^2}} \tag{2}$$

Where *F(t)* is collision load distribution, m is mass of vessel, v is collision velocity of vessel, σ is standard deviation, t is time, μ is half of the collision time. Since it was assumed that the collision load distribution was based on a normal distribution, collision time was set as 6 σ referring a few previous studies [4, 5].

4.2 Comparison between the value of the collision load formula and it from the analytical result

Fig. 13 shows the aspects of collision in Case1. Fig.14 shows comparison of the collision load distribution of the analytical result and the estimated formula. Fig. 15 shows the velocity of the vessel in Case1. Fig. 14 shows that maximum collision load of the analysis was 14920 kN and it of the estimated formula was 9477 kN. The collision load of the analysis was 5443 kN bigger than it of the estimated formula. It was assumed that it was caused by the state that the vessel was rebounded after collision by the transformation of the tower as shown in Fig. 13. To check it, the momentum that the vessel was given by the tower was compared with the impulse calculated by the graph. By the vessel mass of 15000 t and 0.38 m/s in final velocity of the vessel after the vessel was rebounded as shown in Fig. 15, the momentum that the vessel was given by the tower was 5700 kNs. In addition, the area of the graph in Fig. 14 shows the impulse. By subtracting the area of the estimate formula from it of the analytical result, the differences of impulse between the analytical result and the estimate formula was 5842 kNs. From the results, the both values were close. Therefore, it is thought that the collision load distribution of the analysis increased because of rebounding of the vessel.

In summary, in the case that the vessel is rebounded, the collision load could be larger than it of the estimated formula.



0.0s 1.1s 2.3s

Fig. 13 –Collision aspects of Case1

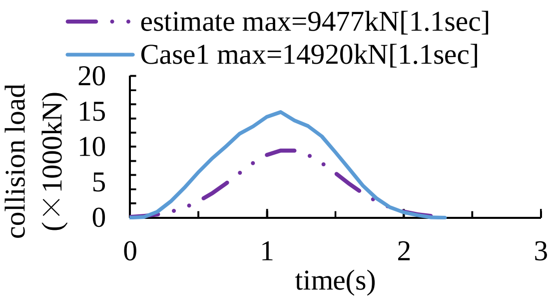


Fig. 14 – Collision load distribution

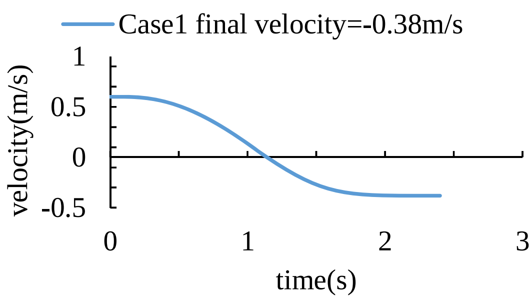


Fig. 15 – Vessel velocity (Case1)

5. Conclusion

In this study, in order to clarify the collision load distribution when the vessel drifted by tsunami collides with bridge structures, collision analyses using FEM were conducted. Taking account of various collision conditions, the parametric analyses which were varied with collision position and direction carried out. And the collision load distribution from the analysis was compared with it from an estimated formula based on a log normal formula. Reviewed in this study are as follow.

(1) Collision load distribution noticeably depended on the transformation of the tower. There was less influence of the change of the tower section on the collision load distribution.

(2) Collision load distribution was noticeably more influences by the state that the vessel inclined to the top and bottom direction than the horizontal direction.

(3) The collision load distribution when the vessel collides in a vertical diagonal direction could be smaller than it when the vessel collides in a horizontal diagonal direction due to the deformation of the vessel.

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