STUDY ON THE ASSESSMENT OF IMPACT FORCE BETWEEN SHIP AND BRIDGE PIER

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SUMMARY

The bridge crossing water way is in the risk of impact by vessel, and thus it is very important to estimate the collision force for the safety of bridge. The impact force between bridge pier and vessel is investigated by numerical simulation and various empirical formulae. The collision response between a 5000t DWT bulk carrier with bulb bow and rigid bridge pier is simulated in the explicit finite element code of ANSYS LS-DYNA. The difference of the impact force between the empirical formulae and FE analysis are discussed. Based on the comparison of the results, the coefficient in the formulae is suggested for obtaining more accurate assessment of impact force.

1. INTRODUCTION

In some circumstance, the bridge pier locates in the waterway, which could be regarded as artificial obstacle in the inland navigation and would be inherently at the risk of possible impacted by the errant transport vessels. Although there exist many methods to reduce the accident of collision between the ship and bridge, it is impossible to avoid completely. In Florida, USA, a bridge beam of Sunshine Skyway Bridge was impacted by ship and fell into the water. Several similar accidences also happened in China.

In the last decades of years' research on ship-bridge impact accidents, the principle methods to calculate ship impact force are experiment, empirical formula and numerical simulation. To quantifying the characteristics of barge impact loads, Meier-Dőrnberg (1983) studied both static and dynamic loading by small scale (1:4.5 to 1:6) model that considered European Type barge. Zhang et al (2010) carried out some experimental studied on drop hammer laterally impacting reinforced concrete bridge pier.

But the collision test generally is performed occasionally because of high cost and the difficulty to carry out. Finite elements method could give reliable and precision result in the study of ship and bridge collision. Hu *et al.* (2005) used FEA software to simulate the head-on collision conditions between rigid bridge pier and vessels with various displacements, in which the relationships between impact force, crush depth and collision dissipated energy were discussed. Yuan and Harik (2008) considered the impact of multi-barge flotilla on bridge piers was also studied flotillas impact against bridge piers by FE analysis.

The numerical simulation method can give reasonable results and a visual failure procedure of the ship and bridge. However, the large amount of effort to establish models and calculation time makes this method inconvenient. Thus, it is commonly that the empirical formulae are adopted during the design of bridge against. In recent years, many scholars proposed the relevant empirical formula method, which is manly divided into two categories: one is the fitting formula achieved according to experimental data, like the formula of Woisin (1976), Saul-Svensson-Knott-Greiner recommended by IABSE (1983), and requirement formula in AASHTO requirement (2007); while the other one is the formula calculated on the basis of some theoretical equations, e.g. the formulae in requirement of TB (2005) and JTG (2004), and Pedersen formula (Pedersen, 1993).

Relative to experiment and FE analysis, the formula method calculates faster, but the accuracy is yet to be assessed for the empirical terms. Wang *et al* (2006) and Wu (2010) investigated the basic process of ship-bridge impact by means of nonlinear finite element, comparing numerical results with various empirical formulae. Sha and Hao (2012) calculated the impact response of barge and bridge pier in FE analysis, and then proposed estimation expression of impact force. Pan *et al* (2016) adopted several common empirical formulae to calculate the collision force of four different bulk carriers impacting bridge piers in various speeds. From these comparisons, it was found that the impact force assessed in these empirical formulae is different with that in FE analysis in some cases.

The empirical formula method has an irreplaceable position during the design of bridge against ship impact in most of circumstance, and the accuracy should be further discussed. The impact response and forces of a 5,000t DWT bulk carrier with bulb bow are discussed according to the numerical results, which are compared with various empirical formulae. Based on the comparison results, the coefficient of empirical formulae is modified for improving the accuracy of assessment results.

2. NUMERICAL ANALYSIS

2.1 PRINCIPLE DIMENSIONS of SHIP

A bulk carrier with 5,000t DWT (deadweight tonnage) is adopted in the collision study, whose overall length, molded breadth and molded depth are 97.0m, 15.8m and 7.5m, respectively. The ship bow model is showed in Figure. 1. The weight of vessel with full and ballast loads are 6,500t and 3,250t, respectively.

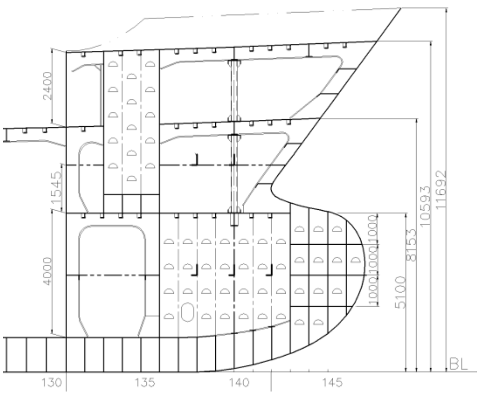
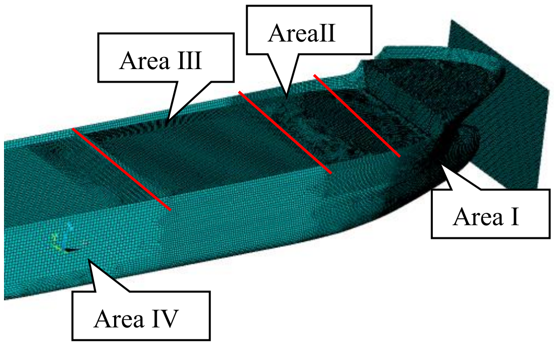


Figure. 1 Section of the ship bow

2.2 FE MODEL

The explicit finite element method of ANSYS LS-DYNA is adopted to simulate the collision process between vessel and rigid bridge pier, in which the Belytschko-Tsay shell element (Belytschko et al, 2006) is adopted to simulate the plate of ship structure, and the beam element (161) is used for stiffeners. The 'automatic surface contact' method is adopted to simulate the contacts between the ship and bridge pier, in which the static coefficient of friction is set as 0.3 and the dynamic coefficient of friction is not accounted for. The mesh size of vessel should be fine enough to obtain reliable results with acceptable computation resource. Tornqvist & Simonsen (2004) and Alsos & Amdahl (2007) recommended that the ratio of length to thickness of shell element is between 5 and 10 to capture the local stress and strain area. The fine mesh size at ship bow is around 100mm at 'Area I' to consider the structural behaviours of buckling and folding in Figure. 2, whose ratio of length to thickness of shell element is around 8. The gradient mesh sizes (Figure. 2 (a)) are applied for the other part with 'Area II' 200mm, 'Area III' 300mm, 'Area IV' 400mm to reduce the element number. The elements with length control are meshed freely by triangle and rectangle shapes. The total number of element is 56757.



(a) Ship impact rigid bridge

(b) Ship bow

Figure. 2 FE mode of the whole ship and the internal structure of the bow

The FE model of the ship is presented in Figure. 2. Poisson's ratio, density and tensile strength of steel material are 0.3, 7,850kg/m^3 and 370 MPa, respectively. The yield stress of plastic material model is defined by

$$\sigma_y = \sigma_0 + \frac{EE_h}{E - E_h}\varepsilon_p \tag{1}$$

where initial yield stress σ_0 is 235 MPa; Young's modulus E is 2.06×10^{11} MPa; hardening modulus E_h is 1.18×10^{9} MPa; ε_p is the plastic strain.

The plastic failure strain of material for bulk carrier is 0.34 according to the element size of the bow structure (Glykas, 2001). Cowper-Symonds formula is adopted to consider the strain rate of material as following (Jones, 1989).

$$\frac{\sigma_0'}{\sigma_0} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}} \tag{2}$$

where σ_0' is the dynamic flow stress relate with plastic strain rate $\dot{\varepsilon}$, and σ_0 is the associated static plastic flow stress. C and P are constant values for ship steel, where C and P are 40.4 s^{-1} and 5, respectively (Jones, 1989).

In NORSOK N-004 (2004), the anti-collision design of bridge is divided as ductile design, strength design and shared energy design as illustrated in Figure. 3, which is dependent on the relative stiffness of the striking ship and struck bridge. The stiffness of bridge pier is generally much larger than that of ship, which causes that the striking ship crush during collision instead of bridge pier. The analysis of bridge against ship impact can be classified as the strength design. Woisin (1976) formula was developed by regression analysis for database of ship-rigid wall impact experiments. Sha & Hao (2012) studied the influence of material characteristic on the deformation of the bridge pier, and the resultant impact force time histories were compared for considering the bridge material as rigid, elastic and nonlinear inelastic. It was found that the impact force is relatively independent of the pier material properties, and the interaction effect between bridge pier and ship is slightly, since the stiffness of bridge is significantly larger than that of ship bow. Moreover, the present aim to investigate the impact force of vessel. Hence, the bridge pier is assumed as rigid in the FE analysis, which ignore the deformation bridge pier and the interaction between the ship and bridge pier. The assessment formula that will be revised does not account for the influence of bridge pier shape. The influence of shape of bridge pier is not accounted for herein, which will be investigated in the future study.

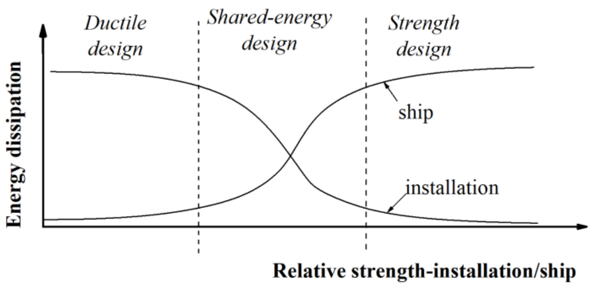
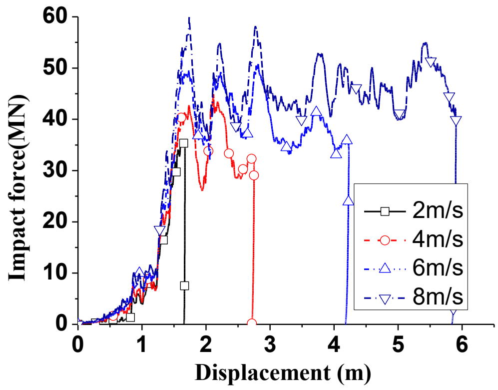


Figure. 3 Design principles base on relative strength

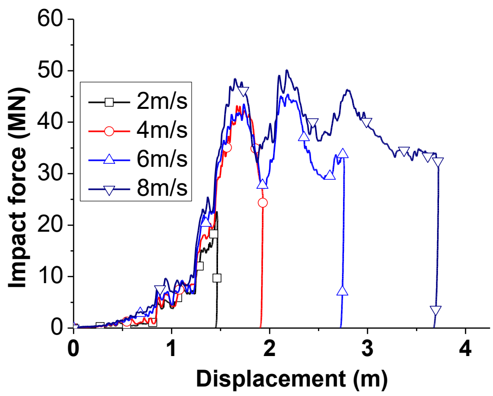
The head-on collision is generally considered as the critical scenario, which was adopted in the experiment by Woisin (1976) for regression analysis and the other assessment empirical formulae in the requirement, e.g. AASHTO (2007) and IABSE (1983). Hence, only head-on collision scenario is considered in the numerical simulations of impact between the ship and rigid bridge wall as shown in Figure. 2 (b). Four impact velocities with 2, 4, 6 and 8m/s are considered for full and ballast loads, which are 6,500t and 3,250t. The initial impact velocity is applied on the whole ship structure. The hydrodynamic mass coefficient is set as 0.07 to account for the influence of added water mass (Wang et al., 2002). There is not any restrain on the striking ship, which is assumed to movement freely. The simulation time for one single run is around between 6 hours and 10 hours that depends on the impact velocity.

2.3 RESULTS ANALYSIS OF FE SIMULATION

Figure. 4 shows the histories of the displacement and impact force of ship with various collision velocities. The indent depths of ship increase with the increment of impact velocities as expected. However, the histories of collision force and depth are very similar at the beginning for different impact velocity, especially for ballast load situation, which means that the stiffness of ship bow is more important for the impact force for the collision velocity under consideration. It is possible to adopt quasi static analysis to assess the impact force between the ship and bridge pier. The first peak force appears when the upper deck crushes in Figure. 6 (a). After the buckling of upper deck, the bulb bow start contact with bridge pier and the impact force drop down.



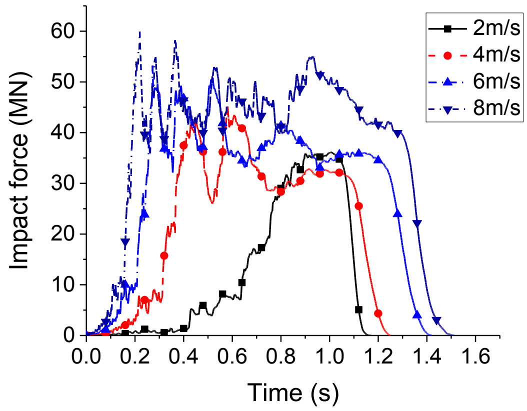
(a) Full load



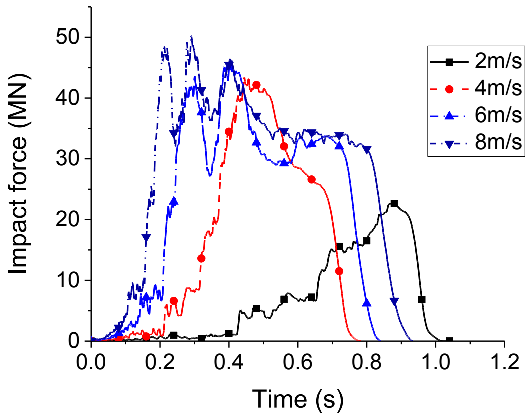
(b) Ballast load

Figure. 4 History of the displacement and impact force

With the increase of ship movement, the structure between transverse frames at bow folds and then crushes, see Figure. 4 and Figure. 5, which cause several wave shape histories of impact force appear between two transverse frames. These positions of wave of impact force are very close for different collision velocities. The histories of impact force at the beginning are similar for various collision velocities. The impact velocity influences significantly on the impact duration and maximum impact load, but slightly on the history of the impact depth and force at the beginning. It seems that relationship between impact depth and load mainly depends on the stiffness of ship bow. This illustrates that the quasi-static method used to assess the maximum force of ship is appropriately. The impact force also depends on initial kinetic energy. Of course, the large impact velocity would cause large indent depth and longer impact duration. However, the impact force between the ship and bridge is still difficult to determinate in the design of bridge piers.



(a) Full load



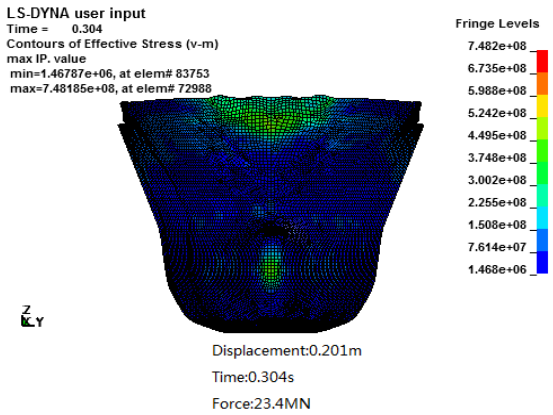
(b) Ballast load

Figure. 5 Time history of impact force

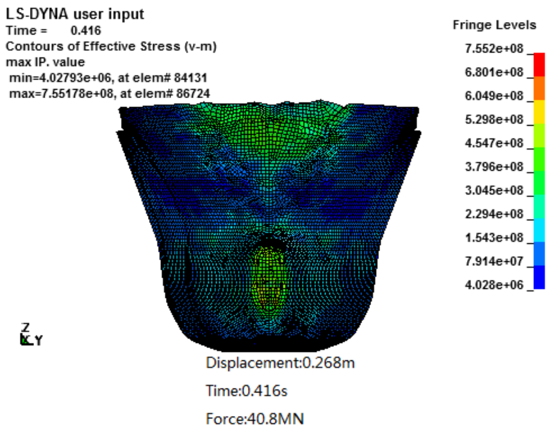
(a) Crush of the upper deck and bulb bow (b) Crush of the upper deck

Figure. 6 Deformations of ship bow (V = 4 m/s)

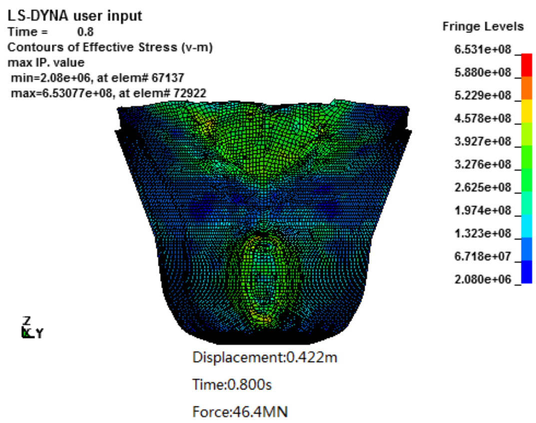
For simplification, the static load is generally adopted in the anti-collision design of bridge pier against ship impact. However, when the dynamic transient analysis using FEM is adopted to calculate the impact force, it is very important to identify that what kind of value should be used in the anti-collision design of bridge piers, since there exist the maximum value, the local average value or mean value during the whole impact process from the history of impact force. Hence, the maximum and mean value of impact force will be compared with that calculated by requirement to identify what kind of the impact value is more reasonable.



(a) Time = 0.304 second



(b) Time = 0.416 second



(c) Time = 0.800 second

Figure. 7 Contact pressure distributions of ship bow

Figure. 7 shows the distributions of equivalent stress of ship bow with impact velocity 4m/s. It can be seen that the contact areas include the upper deck and bulb bow. The maximum contact pressure is not always in the centre of bulb bow, since the upper deck also is involved during collision. This indicates that the impact forces are caused in the both parts, which should be included together in the development of theoretical formulae. The maximum equivalent stresses is 755 MPa in Figure. 7, which is larger than the tensile strength 370 MPa due to the hardening of material, since the failure strain is used to determine failure of structure instead of failure stress.

3. COMPARISONS OF RESULTS BETWEEN DIFFERENT METHODS

After decades of study, several empirical formulae were developed for the assessment of ship impact force. At the present paper, five empirical formulae are investigated and compared with the FE analysis, which are the requirement of AASHTO (2007), IABSE (1983), TB (2005), JTG (2004) and Pedersen formula (1993).

The assessment formulae in requirement of AASHTO (2007) was revised from Woisin (1976) by including the velocity of striking ship, which is given by:

$$F_{\max} = 0.122 \times \sqrt{DWT} \times V \quad \text{(MN)} \tag{3}$$

where $F_{\max}$ is the maximum impact force and DWT is the deadweight tonnage of the striking ship. $V(m/s)$ is the impact speed of the vessel.

IABSE (1983) recommends the empirical formula as follows,

$$F_{\max} = 0.88 \times \sqrt{DWT} \times (V/8)^{2/3} \times (D_{act}/D_{\max})^{1/3} \quad \text{(MN)} \tag{4}$$

where $F_{\max}(MN)$ is the maximum impact force; $V(m/s)$ is the impact speed; $D_{act}(t)$ and $D_{\max}(t)$ are the ship displacement when impacting and fully loaded relatively.

Pedersen (1993) summarized the collision force of striking vessels with deadweight tonnage ranging from 500t to 300,000t according to the research on folding mechanisms of ship bow, which considered head-on collision accidents occurred. The assessment expression of impact force is given by.

$$F_{\max} = \begin{cases} P_0 \cdot \bar{L}[\bar{E}_{imp} + (5-\bar{L})\bar{L}^{1.6}]^{0.5}, & \text{for } \bar{E}_{imp} \geq \bar{L}^{2.6} \\ 2.24 \cdot P_0[\bar{E}_{imp}\bar{L}]^{0.5}, & \text{for } \bar{E}_{imp} < \bar{L}^{2.6} \end{cases} \quad \text{(MN)} \tag{5}$$

where

$$\bar{L} = L_{pp}/275m$$
$$\bar{E}_{imp} = E_{imp}/1425MNm$$
$$E_{imp} = \tfrac{1}{2} m_x V_0^2$$

and P_0 is the impact load during crush of ship bow; $F_{\max}$ (MN) is the maximum load of ship bow; L_{pp} (m) is the ship length between perpendiculars; E_{imp} (MNm) is the energy absorbed due to plastic deformation; m_x (10^3t) means the summary of the ship mass and added water mass that is considered as 5% of ship mass; V(m/s) is the ship impact speed.

TB requirement (2005) provides an empirical formula on the basis of theorem of kinetic energy, which assume that the striking ship's effective kinetic energy acting on the struck bridge equals to the work of the impact force. The formula is presented as.

$$F_{Ave} = \gamma \cdot V \cdot \sin\alpha \sqrt{\frac{W}{C_1 + C_2}} \quad \text{(kN)} \tag{6}$$

where F_{Ave} (kN) is the average impact force; γ (s/m$^{1/2}$) is the reduction factor of kinetic energy, which is assumed as 0.2 when the ship obliquely collides the bridge and is 0.3 when head-on collision occurs; V (m/s) is the ship impact speed; α is the impact angle of ship, which is assumed as 20 degrees; W (kN) is the weight of ship; C_1 and C_2 in unit m/kN are the elastic deformation coefficients of the ship and bridge, respectively, which is defined as the ratio of deformation to impact load. The summary value of C_1 and C_2 is assumed as 0.0005 in requirement of TB (2005).

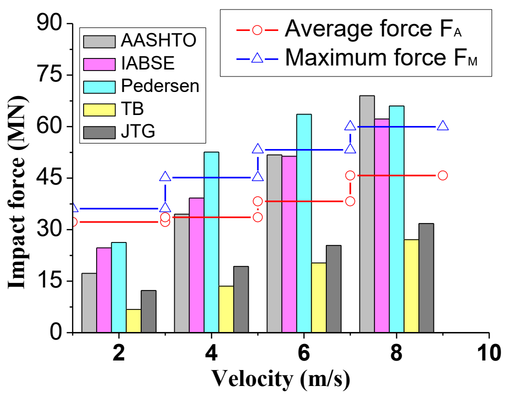
The formula in the requirement of JTG (2004) is proposed that bases on momentum theorem, which is given by

$$F_{Ave} = \frac{WV}{gT} \quad \text{(kN)} \tag{7}$$

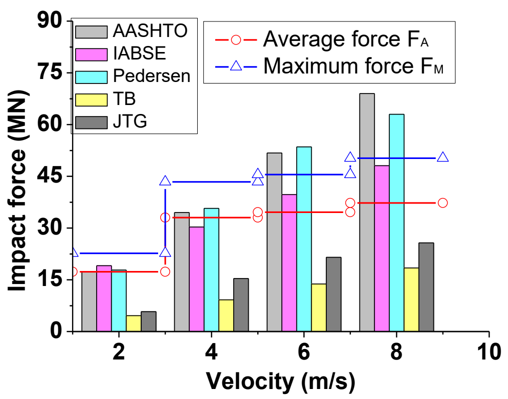
where F_{Ave} (kN) is the average impact force; W (kN) is the weight of ship; V (m/s) is the ship impact speed; T (s) is the duration time of collision, which is assumed as 1 second; g (m/s^2) is gravitational acceleration that equals to 9.81.

The static impact force is often adopted in the anti-collision design of bridge. However, the history of impact force obtained from finite element method bases on the dynamic analysis, if the peak force is adopted during design that would be underestimate the capacity of bridge pier against vessel impact. Hence, the equivalent static impact force is generally adopted in the design of bridge against ship collision (Yuan & Harik, 2009). It was found that the maximum force appear around between 0.1 and 0.2 seconds at the beginning, which is twice of the mean impact force (Woisin, 1976). The peak forces occur between 0.2 second and 0.4 second for impact speed with 4, 6 and 8 m/s, however is around 1 second for 2m/s, see Figure. 5. The time of maximum collision load depend significantly on the impact velocity, but slightly on ship mass for the same type vessel.

Figure. 8 compares the impact forces for different methods, in which the results is presented in bars with different colors for empirical formulae and in line for average and maximum values assessed from numerical simulations. The impact forces in various methods have the same tendency as expected: the larger initial kinetic energy of the ship is, the bigger the forces are. The maximum impact forces calculated by AASHTO, IABSE and Pedersen formulae are close to that assessed in the FE analysis, which increase with the increase of the impact velocity. Because of the formulae in the requirements of AASHTO and IABSE were regressed by experimental data and information from impact accident, which give the maximum impact force. The ship type with bulb bow used in the experiment is similar with that used in the present simulation.



(a) Full load



(b) Ballast load

Figure. 8 Comparison of the impact forces assessed in different methods.

The static impact forces in TB and JTG requirements are significantly smaller than that the average and maximum impact forces in FE analysis, and the other requirements of AASHTO, IABSE and Pedersen formula. TB formulae were developed from kinetic energy theorem and momentum theorem relatively. However, the kinetic energy reduction factor (γ) and elastic deformation coefficients (C_1) in TB formula (Eq. (6)) are assumed as constant. Chen et al. (2013) conducted some experiments research on elastic deformation coefficient. It was found that the recommended values in TB might not appropriate. Du (2015) investigated the dynamic response during ship-bridge impact by means of numerical simulations, reaching a conclusion in which the larger initial kinetic energy of the striking ship is, the lower the transformation ratio of it to deformation energy will be. This means that the bigger initial kinetic energy of the ship is, the lower elastic deformation coefficient will be. The stiffness of ship bow should be different for various ship types and impact velocities.

Hence, the kinetic energy reduction factor (γ) and elastic deformation coefficient (C_1) in TB formula (Eq. (6)) should be different for various kinetic energies to improve the accuracy of assessment. If the results calculated in TB is adopted in the design of bridge against ship collision, which could cause danger situation in the anti-collision design of bridge. It is necessary to revise the formula in TB requirement by considering different elastic deformation coefficient (C_1). According to Eq. (6), the kinetic energy reduction factor γ, is revised as

$$\gamma = F_{Ave-FEM} \Big/ \left(V \sin\alpha \sqrt{\frac{W}{C_1 + C_2}} \right) \tag{8}$$

where the average impact force $F_{Ave-FEM}$ is obtained from FE analysis.

For elastic deformation coefficients, since the stiffness of the bridge pier is significantly larger than that of impact vessel, C_2 is significantly smaller than C_1, and thus C_1 is generally assume as zero. Chen (2006) conducted many calculations on the elastic deformation coefficients for several ship bows, which are presented in Table 1. When a ship crashes against a bridge with an initial velocity, the kinetic energy reduction factor γ means that initial kinetic energy are not totally transformed into the energy due to the deformation and failure of ship and bridge. It can be seen that the elastic deformation coefficients of striking ship decrease as the increase of the deadweight tonnage and displacement of ship. A bulk carrier with 5,000t DWT and 6,500t displacement is considered herein. According to the three C_1 values of bulk carrier (No. 3, 5 and 7), the elastic deformation coefficient almost decreases linearly as the ship deadweight ton or displacement increases. Thus, it can be estimated that elastic deformation coefficients C_1 of the ship can be set to 0.00013, which is used to modify the assessment formula (Eq. (6)). C_2 is the elastic deformation coefficients of bridge, and thus is equal to zero when the bridge pier is assumed as rigid.

Table 1 Elastic deformation coefficients of various ship bows (Chen, 2006)

No.	Ship types	Displacement (t)	V (m/s)	$C_1(m/kN)$
1	79.54m passenger ship	5120	5.35	0.000250
2	5,000t multi-purpose ship	9839	5.0	0.000120
3	10,000DWT bulk carrier	18917	5.0	0.000120
4	10,000DWT container ship	17670	3.0	0.000047
5	35,000DWT bulk carrier	45807	5.0	0.000093
6	40,000DWT oil tanker	50500	6.7	0.000071
7	50,000DWT bulk carrier	62500	3.0	0.000070
8	65,000DWT oil tanker	76189	5.0	0.000022

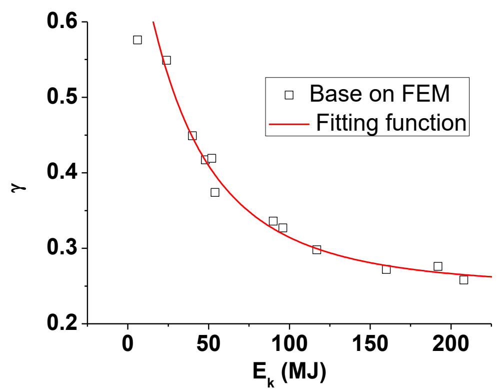


Figure. 9 Kinetic energy reduction factor by fitting power function

To regression of the kinetic energy reduction factor, more load cases with different initial kinetic energy are also considered in the FE analysis. The kinetic energy reduction factor in Eq. (8) is shown in Figure. 9, which decreases with the increase of initial kinetic energy. A power function is adopted as approximating expression, which is given by:

$$\gamma = 5.28\times10^{6}\cdot(E+116.48)^{-3.38}+0.248 \qquad (9)$$

The coefficient in Eq. (9) is regressed by least square method. The coefficient of multiple determinations could be used to assess the approximating accuracy of developed formula, which is given by:

$$R^2 = \frac{SS_R}{SS_T} \qquad (10)$$

where SS_T is total sum of squares and SS_R is regression sum of squares.

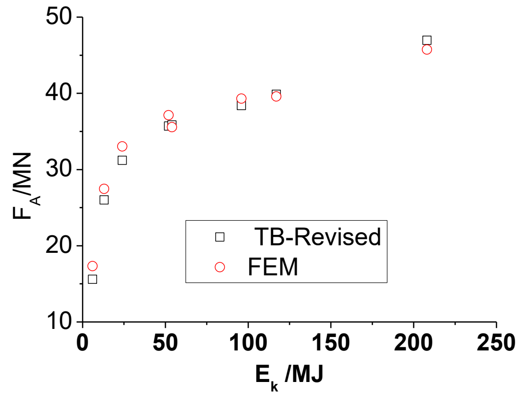


Figure. 10 Comparison between the FE analysis and revised formula from TB requirement

The present mainly focuses on the modification method of formula. Since the modification of TB formula in Eq. (9) base on the bulk carrier with 5,000t DWT, which could be used to assess the impact force for similar type and displacement of ship. Actually, there exist many kinds of types, bows and displacements of ship, which would influence the elastic deformation coefficient. The various ships should be systemically investigated for update the formula in TB requirement (TB, 2005) for application. Meanwhile, it is suggested that the elastic deformation coefficient should be expressed as function of dynamic kinetic energy of striking ship.

The results of the fitting function (Eq. (9)) and FE analysis are shown in Figure.10. The coefficients (R^2) of multiple determinations are 0.98, which illustrates that the fitting functions give well agreement. The average impact force assessed in the formula of TB requirement by revising elastic deformation coefficient are compared with that in FE analysis as shown in Figure. 10. Their results are also very close. The ratio of the mean value and variance of the revised TB formula to numerical simulation are 0.97 and 1.2%, which indicates that the elastic deformation coefficients assessed in Eq. (9) could significantly improve the accuracy of TB formula.

However, the approximating accuracy of regression method by fitting data significantly depends on the range of design sample data. Although the range of kinetic energy of striking ship is already very wide, Eq. (9) is developed by one ship. The stiffness of ship will be different for various type vessel (Woisin, 1976), which also would cause the difference of kinetic energy reduction factor. Hence, it needs to study the kinetic energy reduction factor for different types of vessel bow in the future study.

4. CONCLUSIONS

The collision between ship and rigid bridge pier is simulated in explicit finite element method to investigate the structural response and impact force. The impact forces assessed in FE analysis and several empirical formulae are also compared, which is used to revise the assessment formulae of impact force in TB requirement (TB, 2005). The main conclusions are draw as follows.

1. The histories of collision force and depth are very similar at the beginning for different impact velocity, especially for ballast load situation, which means that the stiffness of ship bow is very important for the impact force for the collision velocity under consideration. It is possible to adopt quasi static analysis to assess the impact force between the ship and bridge pier.
2. The impact forces could be caused by the both upper deck and bulb bow parts, which should be both included in the development of theoretical formulae.
3. There exist many kinds of types, bows and displacements of ship, which would influence the elastic deformation coefficient, and thus should be expressed as function of dynamic kinetic energy of various type of ship by systemic parameter analysis in the future.
4. An expression is developed for assessing the elastic deformation coefficient based on the formula of TB requirement, which could improve the approximating accuracy. From the comparison of results, the modified formula gives well agreement results with that in FE analysis.

5. ACKNOWLEDGMENTS

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