The basic impact load model on deep water pier-ship collision

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ABSTRACT

The collision problem between ship and bridge is a complex multidisciplinary problem. This paper states the frequently-used engineering calculation methods of the ship-bridge collision problem. After analyzing the load characteristic when the pier was impacted by the ship, the author summarizes three kinds of impact load model: triangle load model, half-wave sinusoidal load model, poly-lines load model and then gets the corresponding equations. In order to obtain the impact load characteristic value, the author builds the finite element model with various tonnage ships and bearing stations in different scales in deep water firstly. By using the impact numerical simulation method, this paper cannot only calculate the ship collision equivalent static loads, but also study the relationships between ship collision force, ship mass, tonnage and collision speed. The author can finally get the impacting force calculation formula of the ship impacts the rigid walls. Meanwhile, considering the differences between ship impacts the rigid walls and cushion cap, there is a further analysis of the effect that the cushion cap scale, shape and impact angle put on the maximum impact force and the average impact force.

Key words: Pier; ship impact; load; finite element method
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INTRODUCTION

The collision between ship and bridge is a typical multidisciplinary problem. It relates to the bridge engineering, ship engineering, traffic engineering, collision dynamics and fluid mechanics, etc. At present, the focus of study mainly concentrates on confirmation of impact force, the damage of pier and ship, the development of anti-collide device and the probability of ship impacting bridge, etc. Many study ways of ship-bridge collision have been developed. The collision problem is a strong nonlinear problem, so the author tries analyzing the collision in details is too complex even impossible. This is the background of the simplified analysis method of ship impacting bridge[1].

The simplified analysis becomes relatively complex mainly because of contacting, fluid-structure interaction, etc. This analysis method can be divided into three classes: equivalent ship impacting method, particle spring system method and time course load method. The first method loses sight of ship impacting dynamic effect, which distorts the construction reflection even much more serious. While the second method has already belonged to the dynamic method, which shows the external and interior dynamics process during the collision process. But this kind of method will become complex when the course of ship body changes during the collision process. This kind of method cannot be realized in large-scale structural analysis software. It is also going against the structural design and analysis. So it develops slowly nowadays. The third method adopts loading, which results from the impact force time course calculated by colliding. This kind of method does not radically simplify the analysis method, but it contains the enlightenment of building the simplified analysis method--if people can confirm the experienced impact force time course according to the impacting condition, the structure dynamic reflection analysis would be simple. At the same time, this method can also be accepted easier by engineers. Among the three methods, the last two methods have bigger development space. Time course loading method is also a promising method. In this paper, the author will study the relationships between ship-impacting force, ship mass, tonnage and impact speed, which is based on analyzing load characters that the pier impacted by ship. Meanwhile, the

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author will have a further analysis on effect that the cushion cap scale, shape and collision angle put on the maximum impact force and average impact force.

SHIP IMPACTING DYNAMIC LOADING MODEL
Time course Characteristics of impacting force

Fig. 1 displays the typical impacting force curve. By observing, people can find that the whole time course of impacting force can be divided into three stages: the ascent stage, slowly decline stage before the ship body breaking away and the quick decline stage during the breaking away period. At the beginning of impacting, there will be a short-time and small-loaded slowly ascent stage. This is explained by the fact that the previous contacting is small, so the impacting force is weak and the lasting time is relatively short. After this part of the structure is broken, there will be a wide range contacting. At this time, the impacting force will increase quickly and get to the peak. With the elastic plastic distorting of ship material and the bending, tearing and losing efficacy of structure, the ascent stage gradually declines the time slope. The loading curve will slowly decline when the enormous range of material's plastic distorts and the structure destroyed. But this kind of global decline seems varying sometimes even the obvious platform. This decline stage increases with the impacting speed's increase. At last, the load will incline quickly when the ship body began to break away from each other[2][3].
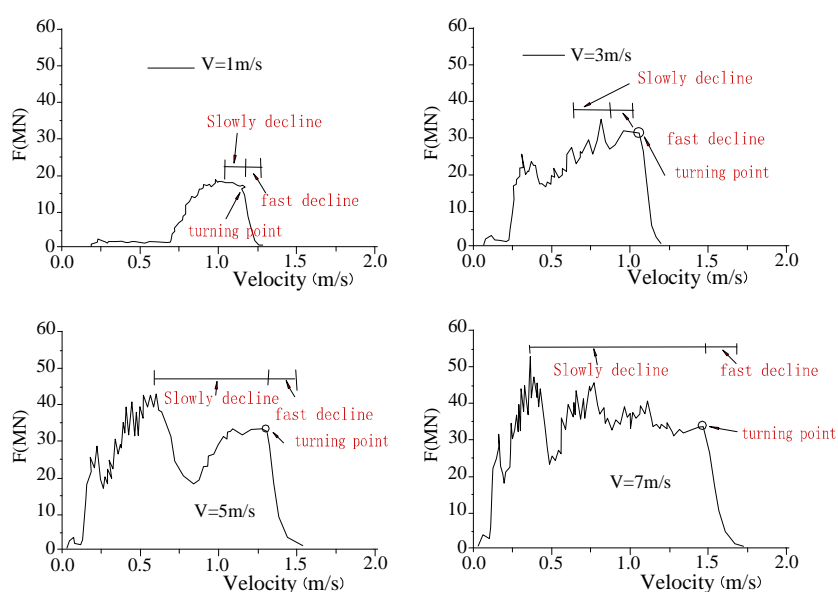

Fig. 1: Characteristics of the typical impacting force changes with speed in post-peak stage

According to the time course observing of ship impacting dynamic, the author finds that the ship impacting force presenting a single peak as a whole. Although this kind of force will present the complex changes because of the differences in the ship structure and the inner structure's crash order. According to this observing result, this paper chooses the mathematical functions as the basic loading model of dynamic design, which can not only reflect the time course's main features of impact force, but also be convenient for the usage of engineering design. According to the characteristic curve of the ship impacting a rigid wall, the author can summarize the following impacting loading model: triangle load model, half-wave sinusoidal load model and poly-lines load model[4].

Triangle loading model

Figure-2 shows the triangle loading model. The load-lasting time t_m is the practical lasting time of impact force time course curve. The largest force P_m is confirmed by equal load impulse principle. t_0 , as the corresponding appearing time of P_m, is the appearing time of practical force peak. There are three parameters: P_m, t_m and t_0 .
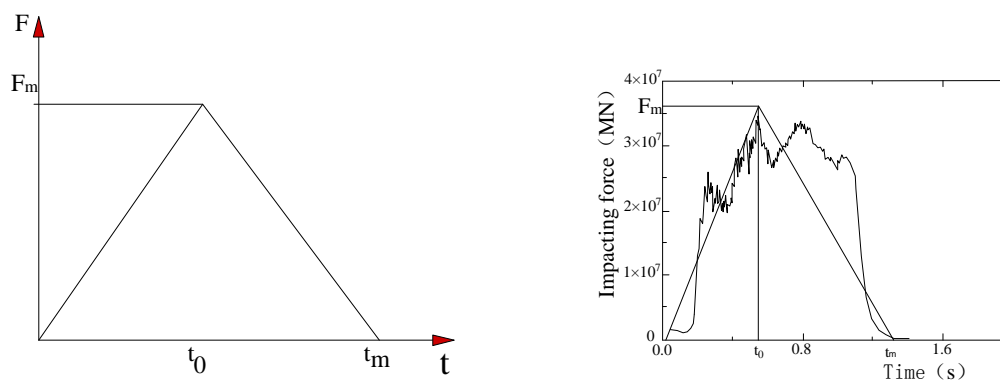
Fig. 2: Triangle loading model

Half-wave sinusoidal loading model

Figure-3 shows the half wave sinusoidal loading mode. t_0, as the corresponding appearing time of P_m, is half of the lasting time of the practical impact force. There are two kinds of parameters: P_m and t_m. Following is the mathematical expression:

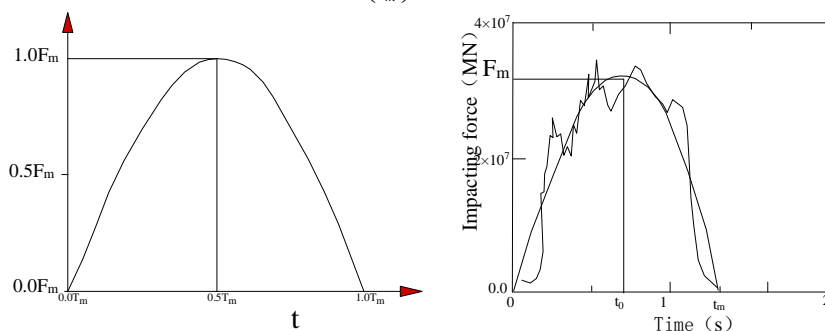$$P = P_m \sin\left(\frac{\pi t}{t_m}\right) \qquad (0 < t < T)$$

Fig. 3: Half-wave sinusoidal loading model

Poly-lines load model

Figure-4 shows the poly-lines loading mode. It is constituted by 3 lines: L_1, L_2, L_3. The peak point of impact force (t_0, P_m) is the practical curve peak. The load time before peak adopts L_1 (1/4 sine wave) as the simulation. The spherical trapezoid curve included in L_1 and timer shaft is equal to the impulse between the load zero and impacting peak. So the load zero can be calculated. L_2, as the load descending stage before the e index curve breaks away which stands for the ship body. L_3, is tangent to the impact force curve quickly descending stage. Load destination t_m is the point of intersection (different from the practical one) between L_3 and timer shaft. L_2 and L_3's intersection point (t_0, P_1) is confirmed by the load impulse (after-peak impulse of practical curve) equivalent principle. There are 5 parameters belonging to poly-lines load model: P_m, P_1, t_m, t_0, t_1. It should be pointed out is, besides superposition between peak and practical curve, poly-lines load including load origin, destination, descent fraction are all the equivalence point, which comes from the equivalence impulse.

The equation of each line:

$$L_1: \quad P = P_m \sin\left(\frac{\pi}{2t_0} t\right)$$

$$L_2: \quad P = P_1 + (P_m - P_1) \exp\left[-c \frac{t - t_0}{t_1 - t_0}\right]$$

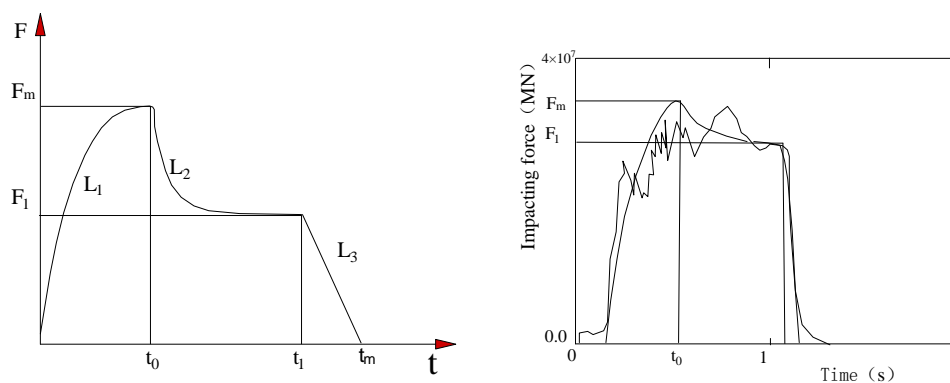$$L_3: \quad P = P_1 - \frac{P_1}{t_m - t_1}(t - t_1)$$

Fig. 4: Poly-lines load model

Parameter c in the formula is to control the descending speed and load platform of slowly descending stage L_2. When the c is relatively small, the load descending speed is relatively slow. So there is mainly no load platform. Conversely, load descending speed is relatively quick and there is an obvious load platform afterward. A large number of impact sample time course show that: the feature of L_2 is when the load has a degree of descending, it will maintain for a period of time at a numerical value. Then a load platform is produced and descending quickly, entering into the L_3.

By observing a plenty of sample time course, we will start from the angle of simplified load model and regard parameter c as constant 10 usually.

FEM MODEL OF CONSTRUCTION COLLISION BETWEEN SHIP AND BRIDGE
The common methods of ship impacting force
The common engineering calculation methods of ship-bridge collision are Minorsk theory (V.U. Minorsk) and experienced formula[5][6][7]. Among the formulas above, the calculation results are relatively different from each other because of the constant confirmation of different calculation methods. Result of the same question and same situation shows that the calculated impact force which adopts the second method is the largest one. While the force which adopts the forth method is the smallest one.

Among the common calculating methods of ship-bridge collision, we consider some simple factors. They are mainly involves impulse formula and energy formula, etc. The result based on the experienced data has some instructing meaning to engineering applications. All the experienced formula do not completely consider the effect of the factors like specific categories, structures and materials from ship, pile foundation, cushion cap and abutment, etc. Nowadays, the global traffic infrastructure develops quickly, the river-crossing even the sea-crossing bridge are building constantly, the structure type of bridge is updating continuously and the tonnage and speed of ship are always increasing. It is harder and harder to meet the engineering design construction's need just by calculating the traditional engineering formula.

In recent years, with the development of nonlinear limited meta-analysis technology and computer hardware system, the ship-bridge collision problem has some new breakthroughs. In terms of the different kinds of collision problem, adopting the nonlinear limited meta-technology can accurately describe the complex geometry shape, material constitutive, damages of ships and bridge. Then people can get a more accurate result. It is much better than the traditional experienced calculating formula[8][9].

Ship impacting rigid wall mode
In order to build the time course load model of ship impacting force, the author regards the rigid things as the typical collision model. After considering the effect of ship tonnage, impacting speed and angle, the author summarizes the time course load model of ship impacting force, which can be used into the structure(e.g. cushion cap) size amending when analyzes the impacted bridge so as to get the purpose of simplified analysis.

The shape and size of practical bridge structure (e.g. searing station) are different from the figures. In order to enhance the feasibility of impacting force course load, the factors like structure, shape and size should be rejected. So the wide appropriate impacting force load mode should be constructed basing on the original force time course curve of ship impacting rigid wall (at this time, the ship body can be contacted with its height), seeing the figure-5.
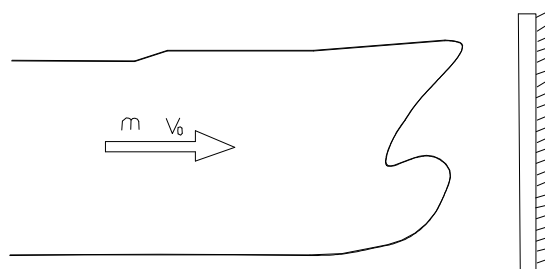
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Fig. 5:   Sketch map of ship impacting rigid wall

Ship model
In this paper's simulation calculation, the basic information of the adopted ship can be seen in table-1.

Table 1*:*   Parameter table of the shape and size of simulating ship

Dead weight capacity (ton)		3000	5000	5000	12000	52300
Displacement (ton)		3962	6710	7700	16700	62000
Main size	Length L (m)	99.9	109.0	137.0	190.0	86.8
	LBP L (m)	94.0	99.8	128.0	182.0	83.0
	Molded breadth (m)	16.8	19.0	22.4	32.26	16.2
	Molded Depth (m)	7.8	7.7	11.0	17.2	4.7
	Draught (m)	6.1	5.0	7.8	12.2	2.8
	Bow height H_s(m)	11.0	11.0	12.0	20.0	7.0
	Block coefficient C_b	0.696	0.776	0.746	0.854	0.837
Bow type		Bulbous	Bulbou	Type V	Bulbous	Bulbous

Ship impacting bridge is an unlimited impacting process. During the contacting process between bow and bridge, the bow structure will be buckled or squashed. In order to get a real impacting process, the author should simulate the shape and structure of the bow accurately. The bow part, which has the directly contact with bridge structure during the impacting process, should get an accurate simulation. Some mesh generations which is far away from the impacting area are relatively thick and can be replaced by steel. The rolled steel strain rate effect and fracture effect also should be considered into the impacting calculation.

The nose of ship is steel structure and it can be disposed into elastic plastic material. The linear mode should be used and the elasticity modulus is $2.1×10^5$MPa. The Poisson's ratio is 0.3. Yield strength is 235MPa. Harden modulus is $2.1×10^2$MPa. Invalid strain is 0.35. In order to consider the effect that the material yield strength got from the strain rate, the author uses Cowper-Symonds mode in materials, C=40.4, P=5.0. The friction coefficient 0.3 is considered into the calculation process[10].

The pile foundation is composed by cushion cap and pile. The cushion caps are mostly rectangle, polygon and polygon with arc. The edges are mostly straight flange or arc in the cushion cap which is vertical to the bridge axes direction. This paper considers the cushion cap mainly rectangle and rotundity. The others are mostly composed by these two shapes. As the maximum ship impacting force is the key to engineering design, considering the impacting force, the author can ignore the effect that rigidity makes to impacting force. So cushion cap's spatial position is fixed as a complete rigidity. The figure 6. shows the limited model of bridge members.
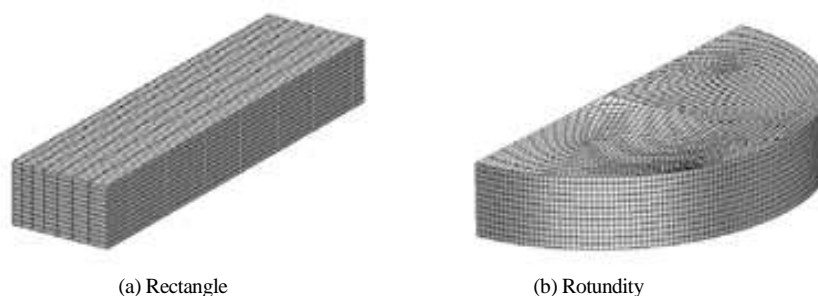

(a) Rectangle   (b) Rotundity

Fig. 6: Cushion cap finite element model

EQUIVALENT STATIC LOAD MODEL
Definition of equivalent static load model
As the second segment mentioned, ship-impacting is a dynamic process. The maximum or peak of impacting force

appears in some time during the impacting process. In the engineering design, such a dynamic impacting process equaling to a static load is needed. Regarding the equivalent load as the whole dynamic process, people should choose a proper way to define the equivalent static load. The author chooses two ways to define it, seeing figure-7. The first way is to choose the peak P_m of the whole time and process. The second way is to choose the population mean P_g of impacting force in time domain.
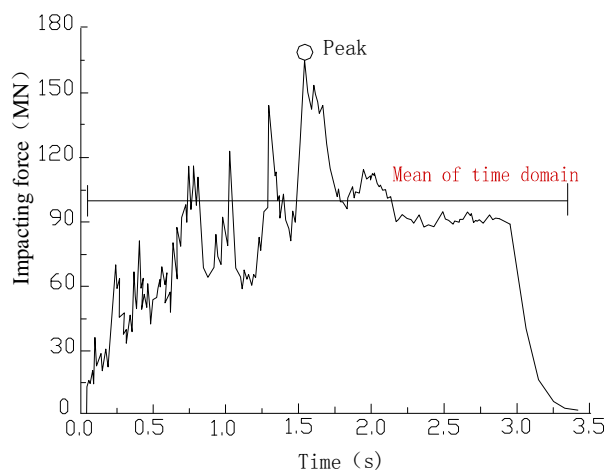

Fig. 7: Definition of equivalent impacting load

Fig.7 is an example of ship impacting force numerical value simulation structure. The beginning time of impacting is t_{g0}. The end time is t_g. The whole lasting time of impacting is Δt_g. If the impulse is I_g during Δt_g time period, the whole average impacting force is $P_g = I_g / \Delta t_g$.

The Fundamental Formula of Equivalent Static Impact Load
Impacting force has been influenced by many factors. When the other factors are relatively fixed, the impacting speed has remarkable influence on impacting force. From the perspective of impacting mechanics, the faster the speed, the stronger the force is and the corresponding duration time is long. In order to clearly reflect the influence of speed on force, the passage has used the finite element model established in the third segment to do simulative calculation of the process ships colliding rigid wall.

Figure 8 has shown how the equivalent static impact load of ships with various weights changed with the change of speed. From the figure, we can see that the equivalent static impact load is increased with the increase of speed. They basically grow in linear relationship. So the straight line equation y=A+Bx can be used for matching.
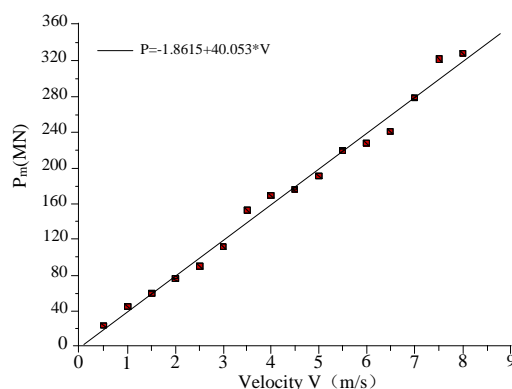

Fig. 8: Relation curve of 50000DWT ship ~V

Generally speaking, when reaching a certain speed, the heavier the ship, the more kinetic energy it has, thus the impacting force will be bigger and the duration time longer. Figure 9 and figure 10 has revealed the relationship between the maximum impacting force and mass and DWT in various speed. From the two figures, we can see that when reaching a stable speed, with the increase of the ship mass, the maximum impacting force is increasing. But they are not in linear relationship. Meanwhile, with the increase of speed, the maximum impacting force of ships in different mass is also
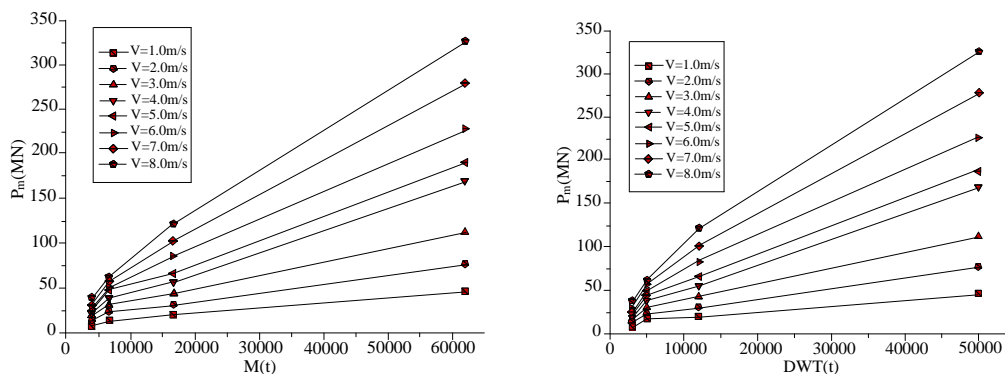
increasing.

Fig. 9: Relationship between the Maximum Impacting Force and M (up)
Fig. 10: Relationship between the Maximum Impacting Force and DWT (bottom)

As the relationship between maximum impacting force and the mass of ship is not in linear line and its increasing trend conforms to the law of power function, so we can use the form of power function to match. Here we choose $y = ax^b$ .The matching can be implemented in two steps. First, match P_m in various speed with M or DWT and we can get coefficient a and index b in various speed. Then match the first step to get index b.   Averaging them and we can get the average $\overline{b}$ .then, make $\overline{b}$ as a fixed index and match again the P_m in various speed with M or DWT. Thus we can acquire a series of new coefficient a corresponding to the fixed index $\overline{b}$.

Through the above matching and simplification, the relationship of maximum impacting power with mass and speed can be shown as:

$$P_m = 0.017 M^{0.7} V$$

Maximum impacting force with the ship's mass and speed can be shown as:
$$P_m = 0.031 (DWT)^{0..66} V$$

In the formula: P_m is the maximum impacting force ships colliding with rigid wall; M is the total mass of ships (ton);DWT is the load tonnage of ships (ton);V is the impacting speed (m/s).

With the same method, we can get the relationship between the overall average impacting force and ship mass or tonnage:

$$P_g = (0.01V + 0.0062) M^{0..66}$$
$$P_g = (0.016V + 0.0117)(DWT)^{0..64}$$

In the formula, P_g is the overall average impacting force ships colliding with rigid wall (MN).

The Correction of Impacting Angle
When considering the relationship between impacting angle and impacting force, the situation that ships collide with cushion cap in 0°(Head-on Collision), 30°, and 45°respectively. Figure 11 shows, in different angles, the time course of the resultant force of tangential impacting force, normal impacting force and impacting force of 12000DWT. By comparing the impacting time course indifferent angles, we can find that, when the angle is changed between 0°and 45°, the impacting duration time reduces with the increase of angle. The time is longest in head-on collision and the time shortest, when the angle is 45°。   This is because, the larger the angle, the smaller of speed component in the normal direction along the cushion cap, thus the shorter the time is. Then let's see from the impacting force perspective, tangential impacting force is very small in head-on collision. When the angle changes from 30°to 45°, the peak of impacting force reduces. The resultant force of normal impacting force and impacting force have the same variation trend. If the impacting angle changes from 0°to 45°, both of the peaks will reduce with the increase of impacting angle.
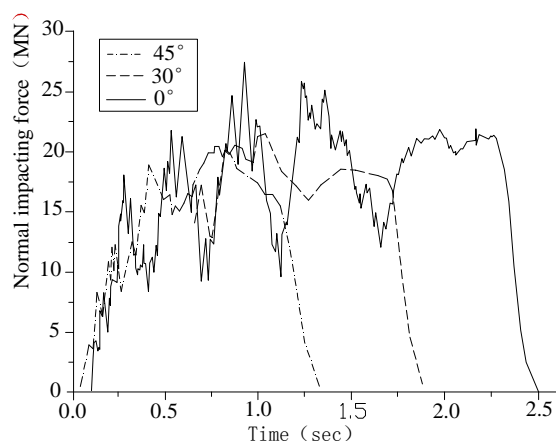
Fig. 11: Normal impacting time course of each angle

By the above 12000 DWT ships colliding the cushion cap obliquely, the influence of impacting angle on impacting force has been analyzed qualitatively. To further acquire the mathematic relation between impacting force and impacting angle, the situation of ships with different tonnages colliding obliquely has been calculated.

By counting and analyzing the result, the correction coefficient of oblique maximum impacting can be shown as:

$$\gamma_M = 1 - \alpha_0 \left(\frac{1}{DWT} \right)^{b0} (1 - \cos\theta)$$

In the formula, a_0 and b_0 are simulation parameters. As for normal impacting force, $a_0 = 28.64$, $b_0 = 0.40$. The relationship of γ_g and γ_M, the oblique impacting correction coefficients of overall average impacting force, is

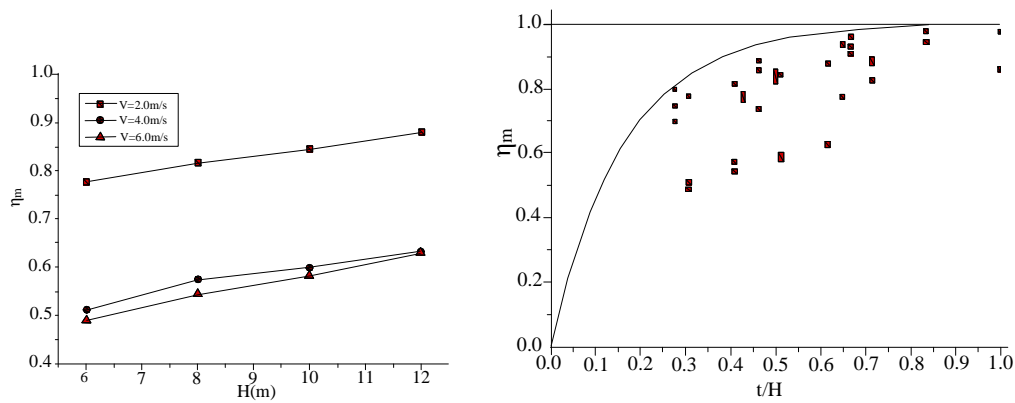$\gamma_g = c_g \cdot \gamma_M$, c_g is 0.64.

The amending coefficient of impacted geometry
Generally speaking, bow's force of impacting the rigid wall is bigger than the force, which owns smaller ship thickness than the body height. In order to reflect the effect what the ship-impacting get from impacted rectangle geometry thickness, the paper need to introduce the amending coefficient:

$$\eta_m = P_{tm} / P_m, \quad \eta_g = P_{tg} / P_g$$

P_{tm}, is the maximum impacting force and P_{tg} is the total average impacting force of the ship-impacting force.

Figure 12 is the result of 50000DWT impacting the 6m、8m、10m 和 12m cushion cap. From the figure the author can find that η_m will increase as the thickness increase when the speed is constant. When the speed changes from 2.0m/s to 6.0m/s, the number of η_m is increasing or descending. η_m, in each tonnage ship doesn't show the unified changing tend, which means η_m is related to the bow structure type and steel. What's more, by analyzing the calculation result of each tonnage ship, the author finds that η_m changes from 0.48 to 1.0. Different speeds make the different changes, especially the large tonnage ship.

Fig 12: Relation of η_m with H for ship 50000DWT (left)

Fig 13: Correction coefficient of P_m for rectangle geometry (right)

Considering the dispersing of impacting force amending coefficient, it is hard to get a unified function expression by using parameter statistic to calculate the 3000DWT~50000DWT impacting amending coefficient. The η_m in each tonnage will increase as the increase of cushion cap thickness. When the thickness increases to a number (bow height), η_m will keep constant if it is 1. From the bridge anti-impacting design angle, the author finds that is harmful to the engineering safety if the η_m is small enough. But it is conservation to ignore the effect. Considering the factors above, η_m can be gotten from the envelope of different force correction coefficient, which can be seen in figure 13. Horizontal axis in the figure is the ratio between impacted geometry thickness t and the bow height Hs. Drawing all kinds of amending coefficients in each calculating condition in the figure, the author can get the function expression which the outer envelope is index 1:

$$\eta_m = \begin{cases} 1 - \exp\left(-\dfrac{6t}{H_s}\right) & \dfrac{t}{H_s} < 1.0 \\ \\ 1 & \dfrac{t}{H_s} \geq 1.0 \end{cases}$$

η_m, is the rectangle geometry amending coefficient of maximum force. *t*, is the thickness of cushion cap(m). H_s, is the bow height.

In terms of total average impacting force, the amending coefficient η_g is:

$$\eta_g = \begin{cases} 1 - \exp\left(-\dfrac{4.7t}{H_s}\right) & \dfrac{t}{H_s} < 1.0 \\ \\ 1 & \dfrac{t}{H_s} \geq 1.0 \end{cases}$$

Similar to the discussion of rectangle geometry, the author can also get the amending coefficient of rotundity geometry:

$$\xi_m = 0.8R^{0.068}$$
$$\xi_g = 0.596R^{0.08}$$

R is the radius of cushion cap round geometry in the formula.

Calculation formula of equivalent static ship-impacting force

After studying the effect what the ship-impacting force get from factors like ship mass, tonnage, impacting speed, angle and impacted geometry, etc. The author summarizes the result of it, which can get the calculation formula of equivalent

static ship-impacting force.

1) Calculation formula of maximum ship-impacting force

$$P_m = 0.017 \cdot \eta_m \cdot \gamma_m \cdot \xi_m \cdot M^{0.7} \cdot V$$

$$P_m = 0.031 \cdot \eta_m \cdot \gamma_m \cdot \xi_m \cdot (DWT)^{0.66} \cdot V$$

2) Calculation formula of total average ship-impacting force

$$P_g = \eta_g \cdot \gamma_g \cdot \xi_g \cdot (0.01V + 0.0062) \cdot M^{0.66}$$

$$P_g = \eta_g \cdot \gamma_g \cdot \xi_g \cdot (0.016V + 0.0117) \cdot (DWT)^{0.64}$$

CONCLUSION

Based on a plenty of impacting force time course sample, this paper summarized and put forward three kinds of impacting force time course load model. These three kinds of simplified basic dynamic modes are all based on the impulse equality, which in order to guarantee the impulse as main feature during the impulse process. Half-wave sinusoidal load mode owns the features like simple style. The other feature is it can reflect the main dynamic characters of ship impacting load. Poly-lines load model based on the original force's time-developing character, adopting the percentage of impulse and time as each stage's control standard. From this paper's simplified result the author can find that the coefficient in modes all can show the function of original impacting speed V, which simplifies the difficulty of getting the confirmed parameter.

Regarding the impact force time course as the load input can overcome the shortcoming: static calculation method of impact force cannot consider the structure quality inertia restrain of the body above impacted part. Such a restrain inner reflection to the upper structure of impacted part should not be ignored. Comparing with the practical impact calculation force load, the poly-lines load mode's error is relatively small among the three kinds of modes. The whole error is smaller than 35%. Meanwhile, the frequency feature of its structure reflection is similar to the practical one.

By using the simulating analysis to conduct a detailed simulating calculation, which is aiming at a series tonnage ship impacting rigid wall with all kinds of speed, the author studies the relationship between force, ship mass, tonnage and impacting speed. At last, the paper gets the force calculation formula of ship impacting rigid wall in deep water. Meanwhile, considering the differences between ship impacting rigid wall and bearing station, the paper makes a further analysis on the effect, which is the force effect from the cushion cap, shape, and impacting angle. The author also gets the practical calculation method which is the factors to ship impacting amending. On this basis, the author puts forward the simplified calculation formula.

The study of this paper provides a basic thinking and load mode for building the bridge-ship impacting design method. There are also some complex factors needed to be studied and developed, such as the effect between bridge member geometrical shape and size, the random factor of ship inner structure and impacting angle. The related mode parameter also needs our constant accumulation and development. Building such a bridge-ship impacting force design theory need a long and persistent study and experienced process. This is just a beginning.

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