Research on New Flexible Bridge Pier Anti-collision Technology

JIANG Peng-fei\textsuperscript{1}, WANG Peng-fei\textsuperscript{1*}, CAO Hong-fei\textsuperscript{2,3,4}, WANG Fei\textsuperscript{2,3,4}

1. School of Highway, Chang'an University, Xi'an 710064;
2. School of Civil and Transportation Engineering, Ningbo University of Technology, Ningbo 315000, Zhejiang, China;
3. Engineering Research Center of Industrial Construction in Civil Engineering of Zhejiang Province, Ningbo University of Technology, Ningbo 315000, Zhejiang, China;
4. Key laboratory of impact and safety Engineering of ministry of education, Ningbo University.

*Corresponding author’s e-mail: 591133753@qq.com

Abstract. With the increase of ship traffic flow, ship size and ship tonnage have increased significantly, while the original anti-collision design of many bridges built in early China has not met the protection requirements, resulting in the increase of the risk of bridge collision by ships. Ship collision with bridges can not only cause huge economic losses, but also result in fatal accidents, leaving a huge hidden danger to the safety of bridges. In this paper, the advanced safety protection concept of ship, bridge and device triple protection is introduced, and a new flexible pier anti-collision technology is used, the additional pile isolation type flexible anti-collision device is proposed. The LS-DYNA dynamic numerical simulation software is used to analyze the dynamic behavior of the ship collision avoidance device. The results show that the anti-collision device using flexible components can store large deformation energy in the process of ship collision. Compared with the theoretical calculation of ship impact force, the ship impact force is significantly reduced after the installation of the new flexible protective device. The flexible anti-collision device proposed in this paper can provide a reliable design for bridge anti-collision.

1. Introduction

With the rapid development of modern transportation, China has built a number of large bridges across the sea and river, as well as a large number of urban river bridges, the construction of these bridges has greatly promoted China's economic and social development, but for ships sailing in rivers and the sea, the bridge is a barrier to safe navigation. The harm of ship collision with bridges is enormous, which causes damage to ships and bridges, and even causes bridge collapse, ship damage and casualties, not only huge economic losses, but also disastrous environmental pollution\textsuperscript{1,3}.

According to incomplete statistics, from 1960 to 2015, the major ship collision bridge accidents abroad, human factors lead to (illegal navigation or improper operation) ship collision bridge accident rate as high as nearly 70%. There are more than 75 million bridges with a total length of 32 thousand kilometers in China. In recent decades, there have been many major accidents of ship collision with bridges. In a short period of one year in 2017, three serious ship collision accidents occurred in
Guangdong Province alone, namely, Hongqili Bridge, Doumen Lianxi Bridge and Modaomen Bridge, which caused significant economic losses. At 1 A.M. on April 6, 2019, an 860m long bridge in the metropolitan area of Belem, the capital of Pará State in northern Brazil, was hit by a fully loaded cargo ship, and the pier column collapsed, resulting in the collapse of about 200m long bridge deck, two vehicles running on the bridge fell into the water, and five people were missing. The accident caused huge casualties and economic losses.

So far, there are many kinds of engineering measures to prevent ship collision. There are twelve kinds of typical structures such as rubber fender, wood structure guardrail, concrete (set) box, anticollision box, gravity pendulum, rope interception type, anticollision pile group, anticollision pier, anticollision guard plate, cofferdam, artificial island and floating system mooring rope type. The AASHto guideline classifies the existing anti-collision facilities into protective plate system, pile support system, steel cofferdam system, independent island system and floating system. Svensson introduced the development of bridge anti-collision devices in the world in the past 25 years, and gave the anti-collision of 18 bridges. Voyiadjis et al. summarized and classified the anti-collision devices for bridges in the United States and other countries. Sun Zhen introduced the application of domestic bridge anticollision device in detail; Pan Jin et al. fitted the relationship between impact force and impact velocity of anti-collision facilities for steel cofferdams. The reasonable selection of bridge anti-collision scheme depends on the navigation width and clearance of the bridge; When the navigable clear width is satisfied, the choice of anti-collision scheme is more flexible, and the attached anti-collision facilities can be selected, while when the navigable clear width is not satisfied, the independent anti-collision facilities should be selected, and the net width of the channel should be occupied as little as possible.

In this paper, a new type of flexible anti-collision device is proposed for the existing bridge, which adopts the advanced safety protection concept of ship, bridge and device triple protection. The collision process between the ship and the anti-collision device is simulated by the finite element calculation of large-scale transient dynamics Ls-dyna, and the dynamic response, force course, maximum ship collision force and energy conversion of the anti-collision device in the collision process of 1000 t cargo ship at a speed of 4 m/s under three different conditions are simulated and analyzed, and compared with the theoretical experience formula. And a reliable design scheme is provided for the anti-collision of the bridge.

2. Introduction of New Anticollision Device

2.1. New flexible anti-collision design technology
The flexible anti-collision facility is mainly composed of an anti-collision ring, an outer steel enclosure and an inner steel enclosure, wherein the outer steel enclosure is used for transmitting and dispersing impact force and turning the sailing direction of a ship; The anti-collision ring has the functions of reducing the collision force, buffering the ship collision process and consuming energy; The inner steel ring is designed to support the anti-collision ring, as shown in Figure 1. Through the coordinated design of the rigidity of the steel enclosure and the flexible anti-collision ring, the synchronous function of each flexible anti-collision ring in the structure can achieve various effects of blocking strong impact, reducing impact force and prolonging impact process time under low load. The outer steel fence is made into a pointed shape with a certain angle in the collision direction, so that when a ship collides with the outer steel fence of the anti-collision facility, the ship is subjected to an outward component force deviating from the original direction, so that the ship has time and space to turn and slide away along the outer side of the anti-collision device, most kinetic energy of the ship is taken away, energy exchange in the collision of the ship with a bridge is greatly reduced, impact force on a bridge pier is reduced, and the effect of 'four or two shifts of To protect the bridge and avoid (or greatly reduce) the damage to the ship.
2.2. Additional pile isolation type flexible anti-collision device

In view of the structural characteristics of arch bridge, it is necessary to protect not only the piers, but also the upper structure. The width of the additional pile isolation type pier flexible anti-ship collision device can be designed according to the protection range of the arch bridge, so that not only the pier but also the upper structure can be protected, and the device is particularly suitable for protecting a deck arch bridge, as shown in Figure 2. And when the channel is not perpendicular to the bridge axis, the risk of ship collision is very large, the need for comprehensive protection of the pier, this paper presents additional pile isolation is a flexible anti-collision technology. The structure design schematic diagram of the additional pile isolation type flexible anti-collision device is as shown in fig. 3, three cast-in-place steel pipe piles are respectively driven at the upstream and downstream ends of the bridge pier, a bearing platform with a double triangle structure is built on the three steel pipe piles, and the floating steel structure flexible anti-collision device is installed outside the two bearing platforms (the bridge pier includes the two bearing platforms) at the upstream and downstream ends of the bridge pier, so as to form the additional pile type flexible anti-collision devices. Based on the rigid design of the outer steel enclosure and the inner steel enclosure, when a ship collides with the anti-collision device, the collision force of the ship is transmitted to the two triangular bearing platforms through the anti-collision ring, so that the steel pipe piles at the upstream and downstream ends of the pier are stressed together to resist the collision force of the ship together.
3. Numerical simulation

3.1. Finite element modeling
The FEMB software of American ETA company is used to complete the pre-processing of the ship collision simulation model. The finite element model includes the pier, the pier anti-collision device and the 1000-ton bulk carrier.

Ship model: shell element is used to simulate and steel is selected as the material model. A 1000t bulk carrier is selected as the ship type for design calculation, as shown in Figure 5, where Figure (a) is a pointed ship, and Figure (b) is a flat head ship. According to the drawing of a 1000-ton bulk carrier provided by a steel structure research Institute, the ship structure is simulated accurately on the basis of simplification. The mass distribution is considered on the model and the weight is balanced reasonably, so that the mass center of the ship model is located in the rear one third of the whole ship, and the structural mechanical characteristics of the shell are ensured to be in line with the reality as far as possible.

Calculation model of anti-collision device: the steel girth and the circular pipe pile in the anti-collision device are composed of shell elements, and steel is selected as the material model. The function of that flexible anti-collision re is to prevent collision and dissipate energy. In the numerical simulation, each flexible anti-collision ring is convert into a discrete element, which is simulated by four nonlinear spring elements and one nonlinear stick pot element, and the material parameters are obtained by fitting the experimental data.

3.2. Computational Boundary Condition
When a ship runs in the water and collides with a bridge pier, the hydrodynamic force actually exists, but it involves complicated fluid-solid coupling calculation. At present, simplified calculation is adopted at home and abroad, for example, the mass of attached water is introduced to correct it; And the boundary conditions should be simplified when they are determined, the main factors should be
grasped and the secondary factors should be neglected. Considering the buoyancy and resistance of the water, it is difficult for the ship to roll over or bow up, so in this calculation model, it is simplified to impose constraints on the vertical displacement of the ship (Y-axis direction). To prevent the boat from rolling over or tilting up the bow. In the actual construction, between the anti-collision device and the pier is free to slide, the calculation of surface contact analysis. In order to fix the outer steel enclosure of the anti-collision device, the outer steel enclosure is connected with the inner steel enclosure through 14 steel cables and combined with the design of a pressure plate in actual construction, so that the relative vertical displacement between the inner and outer steel enclosures is very small. In the calculation simulation, we impose constraints on the outer girth to limit the vertical displacement of the outer girth (this constraint condition is conservative, that is, the calculated impact force is larger than the actual impact force).

### 3.3. Calculation Condition

When the ship mass is constant, the peak impact force is closely related to the impact velocity and impact angle. According to the existing data, the peak value of ship impact force increases linearly with the increase of ship speed. Because the greater the speed of the ship, the greater the kinetic energy of the ship, the more energy the pier will bear when the ship collides with the bridge, and the peak impact force will become larger. The impact angle of the ship will also have a greater impact on the peak impact force. The collision angle of the ship is often affected by the current direction, wind direction and improper operation of the crew and other factors. Therefore, it is necessary to consider the influence of certain impact angle on the impact force in the calculation model.

Based on the above considerations, and access to the relevant statistical data of ships running in the channel, the initial conditions in the numerical calculation process of the model: the initial speed of the anti-collision device is zero, the initial speed of a 1000-ton ship is 4m/s, and the collision angle is respectively considered in two cases of frontal collision (wind and air pressure deviation angle 0°) and oblique collision (wind and air pressure deviation angle 15°). The comprehensive working conditions are shown in Table 1.

| Collision Condition | Angle between transverse direction of bridge and tangent of contact surface | Angle of air flow pressure | Angle of first impact | Initial velocity of impact |
|---------------------|--------------------------------------------------------------------------------|---------------------------|----------------------|---------------------------|
| Additional pile isolation type flexible anti-collision device | 30° | 0° | 30° | 4 m/s |
| Additional pile isolation type flexible anti-collision device | 30° | 15° | 45° | 4 m/s |

### 3.4. Additional pile isolation type flexible anti-collision device

(1) Calculation condition of additional pile isolation type flexible anticollision device for 1000 tonnage pointed bulk carrier in frontal collision (4m/s)

Modeling: The working condition model of the frontal collision of the pointed bulk carrier with deadweight of 1000 tons with the additional pile isolation type flexible anti-collision device is as shown in Figure 5. The ship is sailing along the channel, and impacts the upper part of the inclined plane with 60° sharp angle of the frontal inclined edge of the anti-collision device at the speed of 4m/s.

![Fig.6 Model of Additional Isolated Flexible Anticollision Device for 1000 Tons Point Bulk Carrier in Front Collision](image-url)
Time-history curve of impact force between the ship and the additional pile isolation type flexible anticollision device: As shown in Figure 7, when the ship collides with the additional pile isolation type flexible anticollision device at 0.18 s, the time-history curve of impact force begins to rise from 0 and gradually increases to the maximum impact force of 2MN. Subsequently, the impact force time history curve will appear larger vibration, which is related to the role of flexible elements in the protection process. The final impact force drops to zero at time 0.94 s, at which point the ship is completely separated from the additional pile-isolated flexible fender.

Analysis of energy conversion of that system during impact: the ship initially possesses an initial kinetic energy of 11.9 MJ, i.e. the total energy of the system, as shown by curve C in Fig. 8. As the collision progresses, the kinetic energy of the ship is partly converted into the deformation energy of the ship and the fender (B curve), and the maximum value is about 0.56 MJ, which accounts for 4.7% of the initial kinetic energy. It can be seen that in the process of collision, most of the energy is taken away by the kinetic energy of the ship itself, and can store relatively large deformation energy, so the damage to the ship itself is relatively small.

(2) Calculation condition of additional pile isolation type flexible anticollision device for oblique collision of 1000-ton pointed bulk carrier (4m/s)

Modeling: The working condition model of the 1000-ton deadweight pointed bulk carrier impacting the additional pile isolation type flexible anti-collision device at an angle of 15° away from the channel is shown in Figure 9. The ship moves at an angle of 15° away from the channel and at a speed of 4m/s, and impacts the upper part of the inclined plane with a 60° sharp angle on the front inclined edge of the anti-collision device.

Time-history curve of impact force between the ship and the additional pile isolation type flexible anticollision device: As shown in Figure 10, when the ship collides with the additional pile isolation type flexible anticollision device at 0.32 s, the time-history curve of impact force begins to rise from 0 and gradually increases to the maximum impact force of 2.53 MN. Subsequently, the impact force time history curve will appear larger vibration, which is related to the role of flexible elements in the protection process. Finally, the impact force drops to 0 at 1.08 s, and the ship is completely separated from the additional pile isolation flexible anti-collision device. It is clear that the maximum impact force increases when the ship strikes the additional isolated flexible fender at an angle because the velocity component perpendicular to the impact surface increases as the angle of impact increases.
Analysis of energy conversion of that system during impact: the ship initially possesses an initial kinetic energy of 11.9 MJ, i.e., the total energy of the system, as shown by the curve C in figure 11. As the collision progresses, the kinetic energy of the ship is partly converted into the deformation energy of the ship and the fender (B curve). The maximum value is about 0.9 MJ, which accounts for 7.6% of the initial kinetic energy. It can be seen that in the collision process, most of the energy is taken away by the kinetic energy of the ship itself, and the additional isolated flexible anti-collision device adopts flexible elements, which can store relatively large deformation energy in the collision process, so the damage to the ship itself is relatively small.

(3) Calculation condition of additional pile isolation type flexible anti-collision device for 1000-ton flat-head bulk carrier in frontal collision (4m/s)

Modeling: The working condition model of the additional pile isolation type flexible anticollision device for the front collision of the 1000-ton deadweight flat-head bulk carrier is as shown in Figure 11. The ship is sailing along the channel, and impacts the upper part of the inclined plane with a 60° sharp angle of the front inclined edge of the anticollision device at the speed of 4m/s.

Time-history curve of impact force between the ship and the additional pile isolation type flexible anticollision device: As shown in Figure 13, when the ship collides with the additional pile isolation type flexible anticollision device, the time-history curve of impact force begins to rise from 0 and gradually increases to the maximum impact force of 2.85 MN. The oscillation phenomenon of the whole impact force time history curve is related to the role of flexible elements in the protection process. The final impact force drops to zero at time 0.8 s, when the ship is completely separated from the additional pile-isolated flexible fender.
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Analysis of energy conversion of that system during impact: the ship initially possesses an initial kinetic energy of 11.9 MJ, i.e. the total energy of the system, as shown by curve C in Fig. 14. As the ship collision progresses, the kinetic energy of the ship is partly converted into the deformation energy of the ship and the fender (B curve). The maximum value is about 2.25 MJ, accounting for 18.9% of the initial kinetic energy. It can be seen that in the collision process, most of the energy is taken away by the kinetic energy of the ship itself, which can store more deformation energy, so the damage to the ship itself is relatively small.

3.5. Impact Force Analysis
The determination of ship impact force is an important basis for anti-collision design, which directly affects the safety of bridge structure and the economy of anti-collision scheme. However, the process of collision between ships and bridges is very complicated, which is related to the collision environment (wind, wave, current, etc), the characteristics of ships (the type, size, speed of ships, the strength and stiffness of prow and hull, etc), the bridge structures (the size, shape, material and characteristics of members, etc) and the response of pilots on the spot. It is very difficult to accurately determine the ship impact force on the bridge. However, there are also some empirical formulas for calculating ship impact force, which can roughly evaluate the ship impact force.

According to the empirical formula, the ship collision force is calculated when the ship of 1000 tons collides with the pier at the sailing speed of 4 m/s. See Table 2.

| Bridge Pier | Vessel deadweight tonnage (t) | Ship Displacement (t) | Impact velocity (m/s) | China Bridge Regulation (MN) | China Iron Bridge Code (MN) | American Highway Bridge Code AASHto, 1994 (MN) | Minnock i-Gielle-Voisin formula (MN) | Saul + Knott-Greene (MN) |
|-------------|-------------------------------|----------------------|-----------------------|-------------------------------|-----------------------------|----------------------------------------|---------------------------------|-------------------------------|
|             |                               |                      |                       |                               |                             |                                        |                                 |                               |

Table 2 Ship impact force (theoretical formula)
According to Table 2, the calculated maximum ship impact force is 21.42 MN and the minimum impact force is 6.27 MN when the 1000t ship impacts the pier at 4m/s without anti-collision device. The impact force obtained by the five empirical formulas is highly dispersive, and the average value of the impact force is about 12 MN. The impact force of the additional pile isolation flexible anticollision device proposed in this paper under the conditions of normal collision and oblique collision of a 1000t ship is summarized in Table 3.

| Ship Form               | Ship's deadweight tonnage (t) | Ship displacement (t) | Impact velocity (m/s) | Angle of impact (°) | Maximum impact force with bumper (MN) | Additional pile isolation type flexible anti-collision device |
|-------------------------|-------------------------------|----------------------|-----------------------|---------------------|----------------------------------------|-------------------------------------------------------------|
| Pointed bulk carrier    | 1000                          | 1493                 | 4                     | 0                   | 2                                      | 2                                                           |
| Flat-ended bulk carrier | 1000                          | 1487                 | 4                     | 15                  | 2.53                                   | 2.85                                                        |

It can be seen that the ship impact force is greatly reduced by about 80% after the installation of the protective device. As the impact angle of the ship increases, the ship impact force also increases, because the velocity component perpendicular to the impact surface increases as the impact angle increases. The maximum impact force of flat-head bulk carriers is generally larger than that of sharp-head bulk carriers, because the bow shape of flat-head bulk carriers is not conducive to their being pushed apart by the anti-collision device, which will inevitably produce more plastic deformation, affecting the effect of "four or two tons" of the flexible anti-collision device.

4. Conclusion

Based on the principle of rigid-flexible matching and flexible guiding, a new type of flexible anti-collision device is proposed, which is composed of an outer steel ring, an anti-collision ring and an inner steel ring. The outer steel ring is used to transfer and disperse the impact force and steer the ship, the anti-collision ring is used to reduce the impact force, buffer the ship collision process and energy consumption, and the inner steel ring is designed to support the anti-collision ring.

The maximum ship impact force is 21.42 MN and the minimum impact force is 6.27 MN through five empirical formulas. The average value is about 12 MN, and the impact force can be reduced to less than 3 MN by installing the new flexible anti-collision device, which is about 80%.

In the process of collision, because the anti-collision device uses flexible elements, most of the energy is taken away by the kinetic energy of the ship itself, so the damage to the ship itself is relatively small.

The two new flexible anti-collision devices realize the protection function of the bridge, and can reduce the damage to the ship and the device itself, which is in line with the new concept of bridge anti-collision, and then reduce the risk of ship-bridge collision accidents and the huge losses.

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