



A Performance Study of Anti-collision Device in Ship-bridge Collisions Based on Finite Element Technique

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Abstract. With the development of the transport industry, ship and bridge collision events occur from time to time. To mitigate the damage caused by such events, researchers have studied the effectiveness of anti-collision devices. This paper uses LS-DYNA finite element software to simulate the ship and bridge collision processes with different anti-collision devices. The study analyses the crash avoidance of the anti-collision box in terms of impact force on the bridge abutment, displacement, energy and the impact on the ship. The results indicate that flexible devices, particularly the new airbag devices, provide better protection for bridge piers. However, when considering safety, economy, and collision performance, steel-FRP combination devices have the highest practical value.

Keywords: ship-bridge collision, finite element, anti-collision device

1 Introduction

In recent years, the transport industry has seen a continuous development, resulting in an increase in the number of domestic cross-river and cross-sea bridges. While this has brought convenience, it has also increased the risk of ship and bridge collisions. According to incomplete statistics, hundreds of accidents involving ship and bridge collisions have occurred on the waterway trunk line in recent decades, which brought serious consequences. Therefore, anti-collision devices have been widely studied in recent years as an effective means of protecting ships and bridges from collisions.

Ship-bridge collision is a nonlinear transient problem. The analysis is based on the laws of conservation of energy and momentum. The formulas proposed are often empirical and do not fully consider the collision system, resulting in deviations from reality. The test method produces more accurate results than theoretical analysis, but its preparation often requires significant manpower and material resources. Moreover, the prepared piers and vessels are consumable items that can only be used once and are less environmentally friendly. Therefore, both research methods have limitations. The numerical simulation method provides a more comprehensive analysis of the collision system compared to theoretical analysis and is more cost-effective than experimental

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Y. Qiu et al. (eds.), *Proceedings of the 2024 7th International Conference on Civil Architecture, Hydropower and Engineering Management (CAHEM 2024)*, Advances in Engineering Research 256, https://doi.org/10.2991/978-94-6463-650-5_2

methods. Therefore, it is a better method of research in terms of ensuring the credibility of the data obtained. This paper uses LS-DYNA software to simulate the crash of a 1000-tonne ship to a bridge abutment which protected by various anti-collision devices. The aim of this paper is to investigate the crash avoidance of different collision avoidance devices.

2 Types of Anti-collision Devices

Depending on the materials used, this paper will focus on the crash avoidance of the following four types of anti-collision devices.

2.1 Steel Anti-collision Devices

The steel anti-collision box is currently the most widely used type of anti-collision box in the world. Its research history is the longest. This box can play a certain role in preventing collisions on bridge piers, and its main structure is easy to replace, making construction and maintenance more convenient. The limitations of this type of device are also apparent. Firstly, the hull protection is insufficient, and the ship will still sustain significant damage during a collision with the ship and bridge. Secondly, the steel, which serves as the primary structure of the devices, will inevitably corrode in water, which will eventually affect its collision avoidance performance^[1].

2.2 FRP Anti-collision Devices

Compared to steel anti-collision devices, research on FRP anti-collision devices started later. FRP is a type of fibre-reinforced composite material that is lightweight, strong, has a low modulus of elasticity, and good corrosion resistance. When compared to steel, FRP has several advantages. The use of a Fibre Reinforced Polymer (FRP) anti-collision box can improve the protection of both the ship and bridge. However, it is important to note that FRP also has its limitations. The overall cost of FRP is higher and its strength is relatively low, which may result in a risk of collision between the ship and the bridge abutment, even if the ship is buffered.

2.3 Steel-FRP Combination Anti-Collision Box

The steel-FRP combination anti-collision box is a new type of collision avoidance device proposed in recent years, which combines the advantages of the FRP material and the structural design of the traditional steel anti-collision box. And this type of anti-collision device can effectively reducing the initial construction cost. However, the overall research of this type of anti-collision box is not mature enough, and further research is needed more on the performance advantages and the design of the internal structure.

2.4 Airbag Anti-collision Box

In 2020, Liu Junyi proposed a new type of collision avoidance device called the airbag anti-collision box^[2], which is inspired by the use of airbags in the aerospace industry for heavy falling objects. Airbags are made of material with strong cushioning performance and have the characteristics of being lightweight, occupying small space, and being collapsible. Currently, airbag anti-collision devices are widely used in ship launching, automobile collisions, and have potential for use in ship bridge collisions. However, the initial cost of these anti-collision devices is a concern and further research is needed to analyze their structure and other aspects before they can be applied to actual projects. It is worthy for scholars to focus on this research direction.

3 Overview of Finite Element Modelling

3.1 Ship Models

In the finite element simulation, the ship used in this paper is a 4000 tonne class ship with a speed of 3.0m/s. The model is shown in Figure 1.

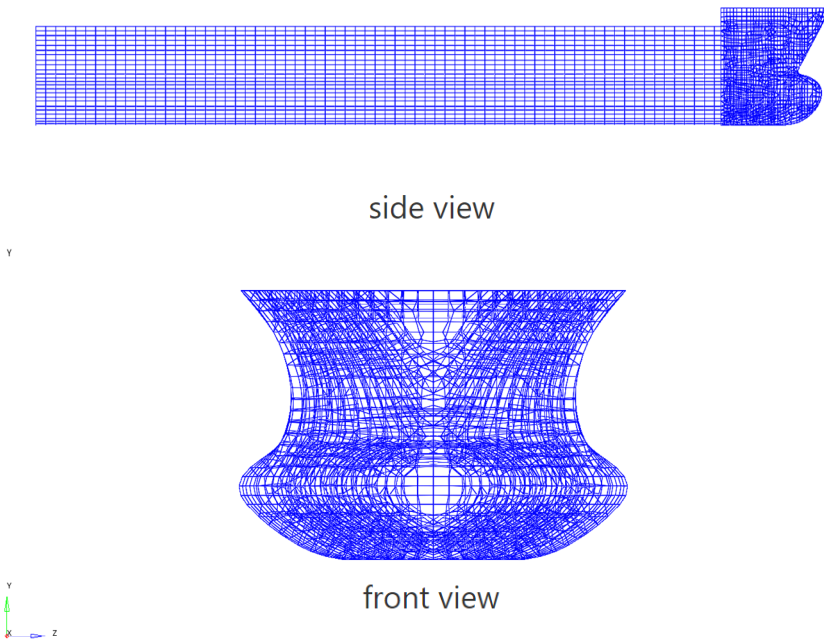


Fig. 1. Ship Finite Element Modelling

In the ship-bridge collision process, the collision between the ship and the bridge abutment is concentrated in the bow part of the ship. The hull's main role is to

provide the mass in the simulation and will not be deformed in the process. So the bow part of the ship adopts the *MAT_PLASTIC_KINEMATIC material model, and the hull part of the ship adopts the *MAT_RIGID rigid body material model. The bow is made of Q235 steel and the material parameters are given in Table 1.

Table 1. Q235 steel Material parameters

| Densities (g/mm ³) | Modulus of elasticity (MPa) | Poisson's ratio | yield strength(MPa) | failure strain |
|--------------------------------|-----------------------------|-----------------|---------------------|----------------|
| 7.89 | 2.07×10^5 | 0.28 | 2.35×10^2 | 0.35 |

3.2 Bridge Abutment Model

The model of the bridge abutment during the simulation is shown in Figure 2.

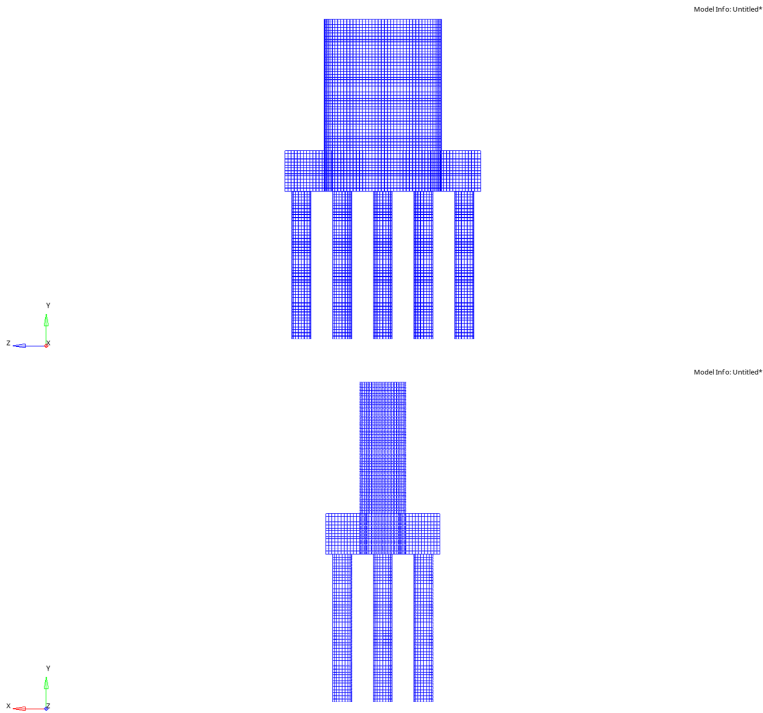


Fig. 2. Finite element modelling of bridge abutment

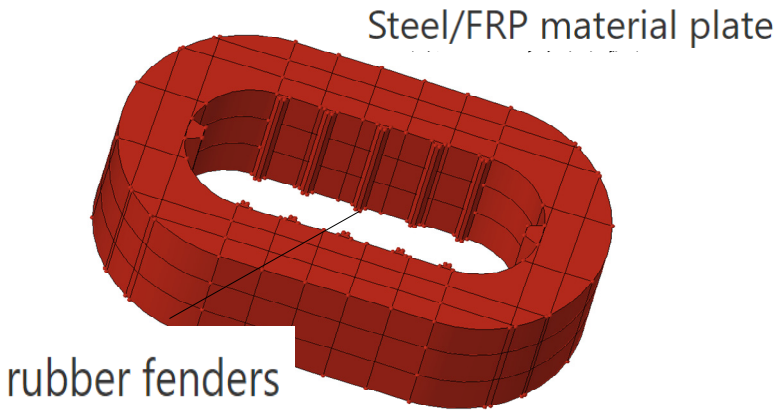
In the simulation of LS-DYNA software, isomorphic models such as HJC model, TCK model and concrete damage model are commonly used to simulate concrete. In the ship-bridge collision process, concrete mainly bears the impact and extrusion load, so this paper uses the HJC model to model the bridge pier^[3], and the concrete material parameters are shown in Table 2.

Table 2. C40 concrete Material parameters

| Densities (kg/m ³) | shear modulus(GPa) | Intensity parameters | | | | damage parameter | | rate effect parameter | |
|-----------------------------------|--------------------|----------------------|------|------|------------------|------------------|-----|-----------------------|-------|
| | | A | B | N | S _{max} | D1 | D2 | EFMIN | C |
| 2350 | 12 | 0.28 | 1.85 | 0.84 | 15 | 0.04 | 1.0 | 0.01 | 0.006 |

3.3 Anti-collision Box Model

The simulation in this paper includes four types of anti-collision devices, of which the steel anti-collision box, the FRP anti-collision box and the steel-FRP combination anti-collision box use the same model appearance, that is shown in Figure 3.

**Fig. 3.** Steel/FRP/combination anti-collision box model

This type of anti-collision device consists of three parts: the outer plate, the rib plate and the rubber fender. For the steel anti-collision box and the FRP anti-collision box, the thickness of the outer plate and the rib plate is 12 mm, the steel anti-collision box is modeled with material model *MAT_PLASTIC_KINEMATIC and the steel is modeled with Q235 steel. The FRP anti-collision box is modeled with material model *MAT_ORTHOTROPIC_ELASTIC [4]. This model accurately simulates the anisotropy of the material and the material parameters of FRP are shown in Table 3.

Table 3. FRP Material parameters

| Densities(g/mm ³) | modulus of elasticity(MPa) | Poisson's ratio | tensile strength (MPa) | failure strain |
|-------------------------------|----------------------------|-----------------|------------------------|----------------|
| 1.56 | 1.03×10 ⁴ | 0.20 | 150 | 0.12 |

The rubber fender in the collision avoidance device uses styrene-butadiene rubber SBR, this part mainly plays the role of fixing the position of the collision avoidance

box and damping, and the *MAT_MOONEY-RIVLIN_RUBBER material model is selected for simulation in LS-DYNA calculation. This model is derived from the Mooney-Rivlin nonlinear incompressible elastic rubber model proposed by Rivlin^[5]. After optimisation analysis, the material parameters obtained are shown in Table 4 below.

Table 4. Rubber fender material parameters

| Densities(g/mm^3) | modulus of elasticity (MPa) | Poisson's ratio | tensile strength (MPa) | C10 | C01 |
|-------------------------------------|-----------------------------|-----------------|------------------------|---------|--------|
| 0.94 | 6.1 | 0.49 | 20.5 | 0.29055 | 0.2804 |

For the steel-FRP combination anti-collision box, the steel plate with FRP coating is used for modelling, the thickness of the steel plate is 8mm and the thickness of the FRP coating is 4mm to ensure that the total thickness of 12mm remains constant, and during the modelling process, the grid of the FRP material should be made the same size as that of the steel plate cells, and the nodes should be shared to ensure that the FRP layer and the steel plate can have the same displacement.

As for the airbag anti-collision box, it was verified by advance calculations that a too small airbags could not provide adequate protection, so the airbag anti-collision box was modelled separately, and the model is shown in Figure 4 below.

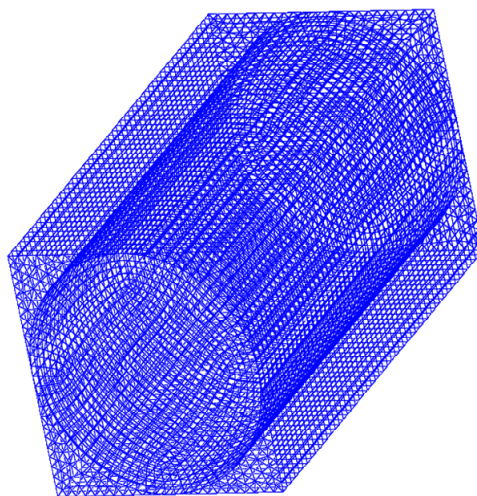


Fig. 4. Finite Element Modelling of Airbag anti-collision devices

Ship bridge collision is a local stress process, only in the impact area of the ship receives a larger stress, so in the computational modelling only in the impact part of the

arrangement of this type of collision avoidance device. This type of collision avoidance device consists of two parts: the outer steel plate and the inner cylindrical air bag. The steel outer plate mainly performs the function of fixing the airbag and preventing direct contact between the ship's bow and the airbag. The airbag mainly performs the function of a buffer. Since there is basically no possibility of secondary collision in the bridge collision, the airbag part of the airbag is selected in the modelling as a closed airbag with better buffering performance^[6]. The steel outer plate is made of Q235 steel with a thickness of 12 mm, and the airbag part is divided into two parts: the fabric material and the internal gas. The fabric material is an orthotropic isotropic linear elastic material calculated using the fully integrated Belytschko-Tsay membrane cell algorithm and the material *MAT_FABRIC (034) is used as the intrinsic model and the material parameters are shown in Table 5.

Table 5. Fabric material material parameters

| Densities kg/m ³ | modulus of elasticity(GPa) | Poisson's ratio | Airbag Size/mm | Airbag thick- ness(mm) |
|--------------------------------|----------------------------|-----------------|-------------------|---------------------------|
| 870 | 9.8 | 0.2 | R3000 | 0.38 |

The internal gases are modeled by using the C-V control volume method^[7] and keywords are defined using *AIRBAG_SIMPLE_AIRBAG_MODEL^[8], with the relevant parameters shown in Table 6.

Table 6. Internal gas-related defined parameters

| Densities (kg/m ³) | gas temperature (°C) | constant volume heat capacity kJ/(kg · K) | constant-pressure heat capacity kJ/(kg · K) | atmospheric pressure /kPa | Airbag in- flation pres- sure /kPa |
|-----------------------------------|-------------------------|---|---|---------------------------------|---|
| 1.195 | 20 | 0.717 | 1.004 | 101 | 101 |

4 Crash results and anti-collision box performance analysis

According to advanced calculation, in addition to the airbag anti-collision box, the other three types of anti-collision devices can complete the process of a whole collision within 2s, the ship can rebound from the impact and tend to stabilise, so the simulation time of the above three types of anti-collision devices is set to 2s; the time of the whole collision under the protection of the airbag anti-collision box is greatly extended, in order to ensure that the whole process can be simulated, the simulation time of the airbag anti-collision box is set to 5s.

After LS-DYNA finite element calculation, this paper will analyse the performance of each anti-collision box in terms of energy, impact force magnitude, bridge abutment displacement and ship response.

4.1 Analyses Based on Impacting Force

The curve of the magnitude of the impact force received by the bridge abutment protected by each anti-collision box is shown in Figure 5.

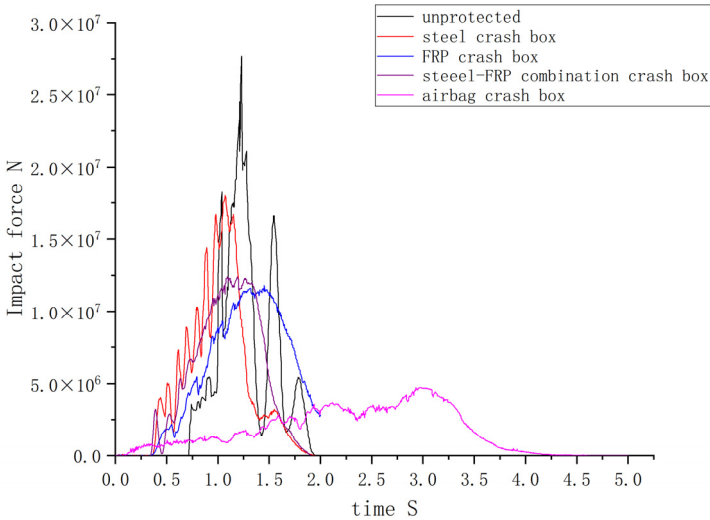


Fig. 5. Impact force curves of bridge piers protected by different anti-collision devices

In terms of peak impact force, the unprotected pier sustained the largest peak impact force of 27.7MN; the peak impact force sustained by the pier protected by the steel anti-collision box is 18.0MN, which is 35.02% lower than the impact force of the unprotected pier; The abutment protected by the FRP box withstood a peak impact force of 11.6MN, a 35.6% reduction in peak force compared to the abutment protected by the steel box; The peak impact force under the protection of the steel-FRP combination anti-collision box is 12.4MN, which is 31.1% lower than the peak force under the protection of the steel anti-collision box; the peak impact force of the bridge abutment under the protection of the airbag anti-collision box is 4.72MN, which is 73.8% lower than the peak force under the protection of the steel anti-collision box. The lower the impact force on the bridge abutment, the better the protection provided by the anti-collision box.

Considering the time of impact, it is easy to see from the graph that the time raise to peak force, from the shortest to the longest, is: steel anti-collision box, steel-FRP combination box, FRP anti-collision box and airbag anti-collision box. The duration of the entire crash, from shortest to longest, is: steel anti-collision box, steel-FRP combination box, FRP anti-collision box, airbag anti-collision box. The longer the time that raise to the peak impact force and the longer the impact lasts, the more pronounced the cushioning effect of the anti-collision box and the less damage to the pier.

From the above two points, it can be tentatively concluded that all four types of anti-collision devices can provide extent protection, of which the airbag anti-collision device has the best anti-collision performance.

4.2 Analysis Based on the Magnitude of the Displacement of the Abutments

Figure 6 below shows the magnitude of horizontal displacement of the abutment under the protection of each anti-collision box.

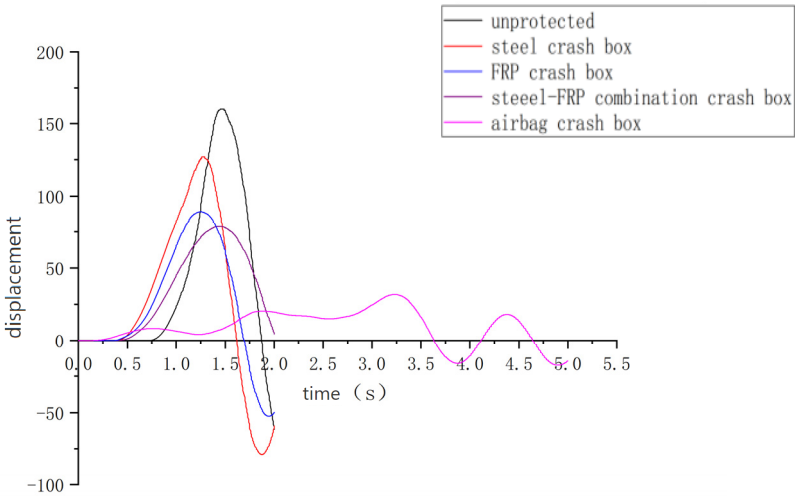


Fig. 6. Horizontal displacement curves of bridge piers protected by different anti-collision devices

Since the impact force during the collision process between the ship and the bridge is essentially all in the horizontal direction, only the horizontal displacement of the bridge pier during the collision is analysed in this paper. From the above figure, it can be seen that the peak horizontal displacement of the abutment under the condition of unprotected abutment is the largest, reaching 160 mm; the peak displacement of the abutment under the protection of steel anti-collision box, FRP anti-collision box and steel-FRP combination box are not much different, which are 127 mm, 78.7 mm and 89.1 mm; and the horizontal displacement of the abutment under the protection of airbag anti-collision box is the smallest, which is only 31.9 mm.

From the point of view of the time to reach the peak displacement, the time to reach the peak displacement of the bridge abutment under the protection of the steel anti-collision box is the shortest, followed by the steel-FRP anti-collision box, the FRP anti-collision box and the airbag anti-collision box, which is consistent with the results of

the order to reach the peak impact force. It can verify the reasonableness of the results.

Therefore, from the point of view of displacement analysis, the airbag collision avoidance box has the best anti-collision performance, in its protection of the maximum displacement of the bridge pier compared with the unprotected pier will be reduced by 80%, compared with the traditional steel collision avoidance box will be reduced by 74%, the effect of collision avoidance is obvious.

4.3 Analysis Based on the Perspective of Energy Transfer

Based on the energy point of view mainly from the piers of kinetic energy and internal energy two parts of the analysis, in the whole process of ship-bridge collision, the energy transferred from the ship to the anti-collision box and piers, and mainly into the kinetic energy and internal energy in two forms. However, since the presence of the airbag breaks the conservation law of the system, and the irregular movement of the gas molecules inside the airbag becomes unpredictable as the impact progresses, the analyses are mainly focused on the internal and kinetic energies absorbed by the pillar, without analysing the deformation or kinetic energies absorbed by the anti-collision device.

Figure 7 shows the variation of the internal energy of the abutment:

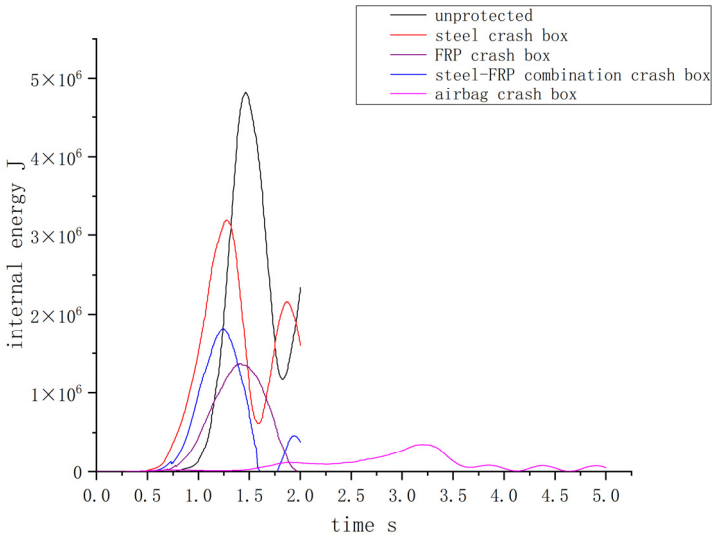


Fig. 7. curves of the internal energy tendencies of the bridge piers protected by different anti-collision devices

From the above figure, it can be analysed that the maximum internal energy absorbed by the unprotected abutment is $4.81 \times 10^6 \text{J}$, the internal energy absorbed by the abutment protected by the steel containment box is $3.19 \times 10^6 \text{J}$, the internal energy absorbed by

the abutment protected by the FRP containment box is $1.37 \times 10^6 \text{J}$. The internal energy absorbed by the abutment under the protection of the steel-FRP combination anti-collision box is $1.82 \times 10^6 \text{J}$, and the internal energy absorbed by the abutment under the protection of the airbag anti-collision box is the smallest, which is $3.44 \times 10^5 \text{J}$.

Figure 8 shows the curves which represent the kinetic energy tendencies of the abutment:

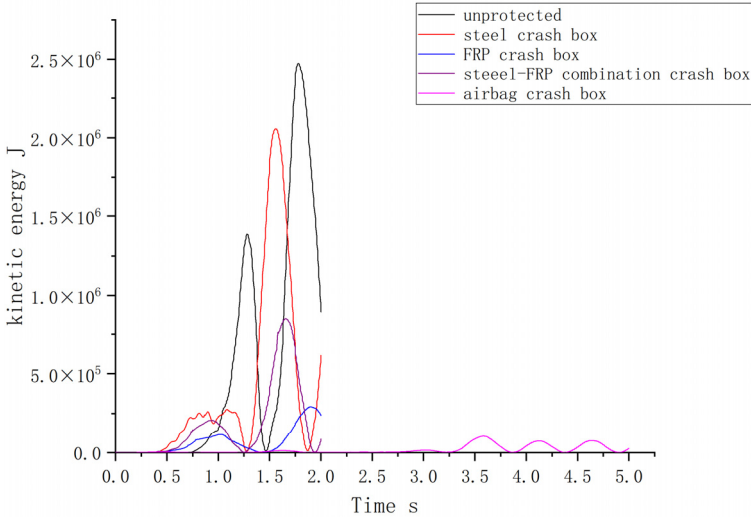


Fig. 8. Curves of the kinetic energy tendencies of the bridge piers under different anti-collision box protections

As can be seen from the above figure, in the case of unprotected piers, the barge converts the most kinetic energy into the piers, which is $2.47 \times 10^6 \text{J}$, whereas under the protection of the airbag devices, the energy of the barge is basically not converted into the kinetic energy of the piers, with a maximum value of only $1.03 \times 10^5 \text{J}$. The kinetic energy transferred to the abutment under the protection of the steel anti-collision box, FRP anti-collision box and the steel-FRP combination anti-collision box are $2.05 \times 10^6 \text{J}$, $2.91 \times 10^5 \text{J}$ and $8.48 \times 10^5 \text{J}$ respectively.

From the above two sets of data, it can be concluded that from the point of view of energy transfer analysis, the airbag collision avoidance box has the best collision avoidance performance, this type of collision avoidance box can greatly reduce the barge energy transfer to the bridge pier, and the energy transfer is basically the main internal energy transfer.

4.4 Analysis Based on Barge Response Perspective

Anti-collision devices should be designed to protect the barge as well as the bridge abutment, so the barge's response to impact is studied in this section.

From the reverse running speed of the barge to analyse the comparison, from the finite element calculation, the reverse running speed of the barge under the protection of the steel anti-collision box is finally 0.89m/s. The reverse running speed of the barge under the protection of the FRP anti-collision box is 1.63m/s. The reverse running speed of the barge under the protection of the steel-FRP combination box is 0.95m/s, and the reverse running speed of the barge under the protection of the airbag anti-collision box is 2.07m/s.

Therefore, analysed from the barge response point of view, the flexible anti-collision box can increase the reverse speed of the barge, which will bring unknown risks. Especially for the airbag anti-collision box, the reverse speed will reach more than 60% of the initial speed, which may cause secondary injuries to the barge. That is risky for a protective device.

5 Conclusion

- (1) Anti-collision devices can protect the abutments and barges effectively.
- (2) Compared to the traditional steel box, the flexible devices have a better protection effect on bridge piers and barges, especially the airbag devices, under which the impact force on bridge piers can be reduced by more than 70% of the impact force under the protection of the traditional steel box. Under its protection, the displacement of the bridge abutment and the absorbed energy are also greatly reduced, so this type of anti-collision device has a good research prospect. However, its excessive flexibility will cause the barge to run backwards too fast after the collision, creating unknown risks. So how to solve and avoid such risks will become the research goal to focus on in the future.
- (3) The crash avoidance of the steel-FRP combination anti-collision box is between the conventional steel box and the flexible FRP box. Compared to the steel crash box, the internal energy transferred to the abutment under the protection of the combined box was reduced by 33.6% and the kinetic energy transferred to the abutment was reduced by 58.6%. The impact force received by the abutment was reduced by 31.1% and the maximum displacement of the abutment was reduced by 29.8%. And the final reverse movement speed of the barge is only 0.95m/s. This kind of anti-collision box inherits the advantages of the two other anti-collision devices of rigidity and flexibility. The rigid structural design avoids direct collision between the ship and the bridge and acts as a cushion. The flexible material reduces the damage to the ship and bridge in the event of a collision. This type of device has a better anti-collision effect than the rigid crush box and effectively reduces the initial construction cost compared to the flexible crush box, which has a better practical value.

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