Analysis of Steel-Aluminum Anti-Collision Device for Pier Protection

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Abstract. Ship-bridge collision accidents often jeopardize the bridge structure, shorten the service lifespan, decrease the safety and durability of the bridge and cause losses in the seismic capacity. Therefore, it is necessary to conduct research and simulation on anti-collision facilities for piers. Aluminum foam has significant advantages in anti-collision and energy absorption performance as a new type of foam material. This paper uses ANSYS/LS-DYNA to simulate the process of a ship-bridge collision and analyzes the energy absorption effects of the steel-aluminum anti-collision sandwich structure.

Keywords: Foam aluminum; Ship-bridge collision; ANSYS/LS-DYNA.

1. Introduction
Foamed aluminum [1], [2], [3] is a category of material that can significantly absorb energy by undergoing large plastic deformation. In recent years, substantial studies have demonstrated that aluminum foam can effectively protect concrete from hitting impact. Schenker [4] conducted both experimental and numerical analysis to explain the different performance of a concrete slab with and without protection from aluminum foam. The experimental results showed that the concrete slab experiences a complex ‘spring back behavior’ under the impact load due to inadequate constraints, and aluminum foam can protect the concrete slab better. Ahmed K. Taha [5] simulated numerical blasting tests on concrete slab under aluminum foam protection using autodyn-3d software. The concrete slab was protected by the aluminum foam from the explosion and the maximum deflection was dramatically reduced according to the results. Xia [6] proved that foam aluminum can minimize the damage of explosion on concrete slab. In this paper, an anti-collision device is designed based on the energy absorption property of aluminum foam, and the effect verification will also be included.

2. Finite Element Modeling
2.1. Geometric Model
2.1.1. Geometric model of pier. The Geometric model of pier is created according to a bridge on the Yangtze River in southern China. The pier is 50m in height with a cuboid base of size 4.5m×18m×13.5m at the bottom. The two legs of the double-leg thin-wall pier were connected by a 7m×7.5m×2m coupling beam.
2.1.2. Geometric model of ship. The model of the impact ship selected in this simulation is the standard ship type of the Three Gorges 2000DWT class bulk carrier. The side elevation of the selected ship is shown in Figure 2.

2.1.3. Geometric model of steel-foam aluminum anti-collision device. The steel-foam aluminum anti-collision device was attached to the front surface of the coupling beam with a triple-layer sandwich structure of 7m in length and 2m in height. The individual thickness of front and rear steel plates and the foam aluminum layer in between are 6cm and 40 cm respectively. The total thickness is 0.52m. The dimensions of the sandwich structure are shown in Figure 3.
system as shown in figure 4.

![Figure 4. The finite element model of the whole system](image)

2.2. Material Model

2.2.1. Concrete material model. The concrete model is HJC (*MAT_JOHNSON_HOLMQUIST_CONCRETE) (Holmquist-Johnson-Cook) material model, which can be used to simulate concrete under high strain, high strain rate and high pressure.

2.2.2. Foam aluminum material model. LS-DYNA has a wide range of models describing foams which are available for use. The crushable foam material model(*MAT_CRUSHABLE_FOAM) is specially used in modeling compressible foam, with optional damping and tension cut-off functions. Unloading is fully elastic. Tension is considered to be completely elastic-plastic.

2.2.3. Steel Material Model. To simplify the analysis, assumption has been made with same plastic dynamic material model for the steel plate and the bow using “*MAT_PLASTIC_KINEMATIC”, which is suitable for simulating kinematic hardening plasticity and can optionally include rate effects. The material model used in this simulation is summarized in Table.1.

| Material      | $\rho$(g/cm$^3$) | $E$/GPa | Poisson's ratio |
|---------------|-----------------|---------|-----------------|
| Concrete      | 2.440           | 30      | 0.25            |
| Foam aluminum | 0.687           | 2.25    | 0.3             |
| Steel         | 7.85            | 206     | 0.3             |

2.3. Model SETUP

2.3.1. Elements Type Setup. All parts of the model are created by SOLID164. For PART of foam aluminum material, redefined the KEYOPT(1)=2 is necessary, which means the one point integration by default of SOLID164 was changed to fully integration. With this setting, the “negative volume” and the hourglass energy during the calculation can be avoided. The equations solved for SOLID164 element set as Lagrange method.

2.3.2. Load and boundary conditions. The impact ship was set at a speed of 3m/s as the load of the
entire system and the impact point was targeted at the center of the front plate. In order to simplify the
calculation, a fixed constraint is imposed on the pier at both top and bottom of the pier because a
considerable constraint is provided by the girder to the pier, as shown in figure 5 and figure 6.

![Figure 5. Constraints on top of pier](image1)
![Figure 6. Constraints on bottom of pier](image2)

3. Calculation and Analysis

3.1. Accuracy Verification of Calculation Model

The ship collision force calculated from the simulation model is compared with three other different
calculation methods to verify the accuracy of the model. The details of the comparison are illustrated in
table 2.

| Code for Design on Railway Bridge and Culvert (RPC) [7] | Woisin formula [8] | AASHTO formula [9] | Numerical simulation result |
|--------------------------------------------------------|-------------------|------------------|-----------------------------|
| ship collision force (MN)                              | 16                | 17.6             | 14.7                        | 16.28                       |
| variance (MN)                                          | -0.28             | -1.32            | +1.58                       | —                           |
| Variance Percentage                                    | 1.71%             | 8.10%            | 9.70%                       | —                           |

From the data comparison in table 2, the results of different calculation methods of ship collision force
on bridge vary significantly from each other. The numerical simulation result is very close to the
calculation result from the code for design of railway bridges and culverts (RPC ), and it is slightly
lower than the calculation result with the Woisin formula and slightly higher than the calculation result
with the formula given by AASHTO. Generally, the calculation result of ship collision force is in the
acceptable range. The model is credible.
The global energy transfer and transformation in the impact process can also be used to illustrate the
correctness of the model.
Figure 7. Energy and time curve of the global (unit: s in X axis, MJ in Y axis)
Figure 7 shows the global energy change curve of the whole system. The total energy in the impact process remains constant and the hourglass energy is approaching to 0. The hourglass energy of the model is well controlled. The system obeys the energy conservation law.

3.2. Analysis of Anti-collision Device
Most of the energy was absorbed by the anti-collision device which underwent a large deformation. Figure 8 shows the energy absorption of each part of the anti-collision device.

Figure 8. Energy and time curve of the global (unit: s in X axis, MJ in Y axis)
From figure 8, the energy absorption of the front plate is 2.26MJ and the energy absorption of the aluminum foam is 4.08MJ. For the rear steel plate, the energy absorption is only 3056.6J, which Energy absorption effect is insignificant. The total energy absorption of anti-collision device is 6.35MJ, accounting for 88.2% of the total energy.

3.3. Protective Effect of Anti-collision Device on Piers
The anti-collision effect of the aluminum foam anti-collision device and the protection for the pier and ship are investigated through the comparison between the calculation of collision between the ship and the pier with and without anti-collision device as shown in table 2.
The pier and the impact ship were well protected by the anti-collision device. The protective mechanism is to expand the impact range of the aluminum foam through the front plate, so that more foam aluminum will participate in deformation and cooperate to deform and absorb energy. The deformation process is essentially an energy absorption process, which can reduce the impact of collision on the ship and pier.
Table 3. Comparison of calculation results of two conditions

|                              | Without anti-collision device | With anti-collision device | Reduce value | Reduce percent |
|------------------------------|-------------------------------|----------------------------|--------------|---------------|
| Maximum stress of impact point on pier (MPa) | 93.6                          | 29.7                       | 63.9         | 68.2%         |
| Maximum acceleration of pier (m/s²)        | 31.4                          | 12.8                       | 18.6         | 59.2%         |
| Energy transferred to piers (MJ)            | 2.46                          | 0.21                       | 2.25         | 91.4%         |
| Energy absorbed by ship deformation (MJ)    | 3.20                          | 0.10                       | 3.10         | 96.8%         |
| Residual kinetic energy of ship (MJ)        | 1.2                           | 0.5                        | 0.7          | 58.3%         |

4. Conclusion

This paper draws the following conclusions by using the LS-DYNA software to simulate the collision between the ship and the pier with anti-collision device:

1) When a 1600dwt class bulk carrier is colliding with a pier with anti-collision device at a speed of 3m/s, the collision process occurs extremely quickly, the entire collision process is completed in 0.6s, and the peak collision force of the ship is 16.28MN.

2) During the impact, most of the energy is absorbed by the anti-collision device, with a value of 6.35MJ, the main energy absorption is the front steel plate and the foam aluminum core layer, the value are 2.26MJ and 4.08MJ respectively.

3) The anti-collision device can provide the significant protection during collisions. Compared with the collision without anti-collision device, for the pier, the maximum stress of the pier is reduced by 68.2%, the acceleration is reduced by 59.2%, and the energy transferred to the pier is reduced by 91.4%. For ships, the energy absorbed by the ship's deformation is reduced by 96.8%, and the residual kinetic energy of the ship is reduced by 58.3%.

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