

# ANALYSIS ON EFFECT OF BEARING TYPES ON CONTINUOUS GIRDER BRIDGES UNDER SHIP COLLISION

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## ABSTRACT

After analyzing the existing simplified methods of ship-bridge collision and comparing their pros and cons, a relatively safe simplified analysis process is put forward. The time-history curve of the ship collision force obtained from the ship-rigid wall collision simulation using the software LS-DYNA is put into the whole bridge dynamic model in SAP2000 and then dynamic response analysis of the whole ship has been carried on. Respect to the bridge with ordinary fixed bearings and seismic isolation bearings, the influence of the bearing type on the key structure of the bridge are analyzed. Then the features and rules of the continuous bridges dynamic responses with different bearings under different ship-bridge collision angle and velocity are obtained.

**Keywords:** *Continuous Bridges, Ship Collision, Bearings, Numerical Stimulation, Collision Angle, Bearing Type*

## 1. INTRODUCTION

The bridge is an important transport hub of the traffic system. In recent years, with the rapid development of China's economy, more and more long-span bridges over rivers and straits have been built, and capacity, quantity and speed of the ships are constantly growing, which increases the potential risk of ship-bridge collision. The ship-bridge collisions happen frequently both at home and abroad.

The process of ship-bridge collision, which belongs to the area of impact dynamics, is exceptionally complicated. The dynamic load of the collision interface is determined by the transmission process of the coupled waves between the collision objects. The transmission of the wave varies due to the difference of the structures and material of the ships, the bridge piers and the safeguard facilities. Under ship-bridge collision, many factors, such as the weather, wind, waves and water current, will influence the collision force and the responses of the bridge structure. The features of the ships including the type, size, internal structure and speed and angle of the ship- bridge collision, size and material of its components are also important factors to be considered.

The bearings are connected the girder and the pier. Theory and experiment show that the bearing

type has a great influence on the bridge dynamic responses. In the study of bridge seismic resistance, the flexure supporting structure and power – dissipation structure can reduce the bridge dynamic response under earthquake by lengthening the structural period and consuming energy. Though massive research on the technology of seismic absorption and isolation has been done by domestic and foreign scholars[1-3], influence of the bearing, as the joint of the upper and lower structures, on the collision force under the ship-bridge collision has not been studied. This article analyzes and studies the continuous bridges with ordinary fixed bearings and seismic isolation bearings respectively under the ship-bridge collision.

## 2. SIMPLIFIED ANALYSIS METHOD OF BRIDGE-SHIP COLLISION

To simplify the analysis and exclude influence of many uncertain factors so as to focus on the major problem, regarding the time-history curve of the ship-rigid wall collision as the dynamic load, this article studies the response of continuous bridges with different bearing types under the ship collision. The simplified analysis process is shown in Figure 1. In phase 1, the basic parameters of the ship model are determined according to its size and structure and a finite-element ship model is built with PATRAN. To stress the characteristics of the ship under a collision, a ship-rigid wall collision

model is used to study the local collision effect. Through the analytical software LS-DYNA, the time-history curve of the collision force under the ship-rigid wall collision is obtained. In this phase, the characteristics of the ship in the collision, not the response of the bridge structures, need more attention[4]. It is conservative to replacing the ship-bridge collision force with the time-history curve of the ship-rigid wall collision force. In phase 2, put the time-history curve of the ship-rigid wall collision force into the continuous bridge beam element model built with SAP2000 for dynamic response analysis of the whole ship. Then the responses of major parts are obtained and a conclusion is drawn.

$\sigma_e / \sigma_0 = 1 + (\dot{\epsilon}_e / D)^{1/q}$ , and the strain rate coefficient of the mild steel in the ship bow is  $D = 40.4$ ,  $q = 5$ .

In this course, MSC. PATRAN and FEMB are used in early phase, and the model of Patran is shown in Figure 2. Then LS-DYNA is used as the solver for the analog stimulation of the ship-rigid wall collision.

Table 1  
Major Parameters And Size Of The Colliding Ship

Ship type	Length (m)	Breadth (m)	Depth (m)	Draught (m)	Load (t)	Displacement (t)
Cargo ship	121.0	20.0	9.0	6.0	9440	11900



Figure 2: The Finite Element Of Ship

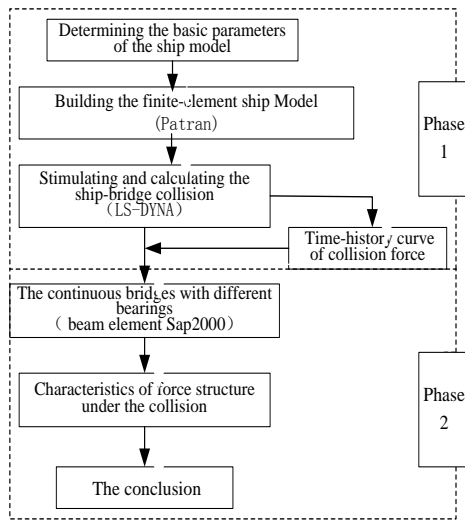


Figure 1: Flow Chart Of Simplified Analysis Method

### 3. CALCULATION EXAMPLES AND ANALYSIS

#### 3.1 The Finite Element Model Of The Ship

The ship used in the article is cargo ship 10000DWT, whose parameters are shown in Table 1. The ship bow, which produces a large deformation to energy consumption in the collision, is stimulated more intensively with elastic-plastic steel as the stimulation material, whose parameters are identical to that of the actual bow. The other parts of the ship, far from the collision area, are unlikely to deform. In order to save the effort of model building, calculating time and memory space, the structure is stimulated with relatively rough finite-element mesh and rigid material.

Since the collision is transient and the steel of the bow has large strain rate, the influence of material strain rate should be taken into consideration. In this paper, Cowper-Symonds model is used for the strain rate, which is [5]

#### 3.2 The Finite Element Model Of The Continuous Bridges With Different Bearing Type

The bridge used in the calculation is one continuous bridge in China with the spans of  $5 \times 50$ m. The elevation is shown in Figure3. The bridge is made up of main girder of box section, double-column pier with tie beam and Group pile foundation. No. 4 pier is fixed, while the others are mobile. The ship hits No. 3 pier from different angles. The elevation and side view of the piers are shown in Figure4. No. 3 pier is a 2-meter-diameter round section and a dumbbell-shaped abutment. The foundation type is double-row piles, and six 1.8-meter-diameter friction piles are fixed to each abutment according to the width of the bridge. The pile is 56.8 meters long and is inserted into the ground made of medium sand, fine sand and silt. The effect of the foundation soil on the pile foundation is stimulated with six springs, and the rigidity coefficient of the spring is got through “m” method in The Design Specifications of Bridge and Culvert Foundation (JTG D63-2007). Since the influence of the ship collision is local, it is not necessary to consider the influence of the neighboring span. The analytical model of the whole bridge force is built with SAP, as is shown in Figure5. Cap is simplified rigid body, main beam and pier is simulated with beam element, bearing is simulated with level nonlinear element. Calculate and analyze three whole bridge models with different bearing type.

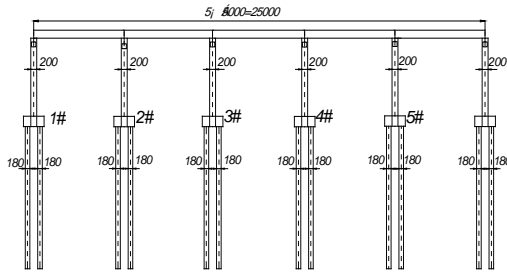


Figure 3: Elevation Of The 50-Meter Continuous Bridge

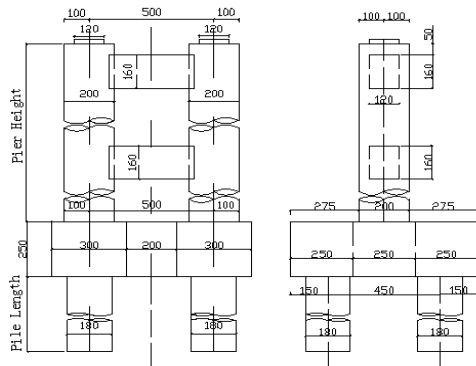


Figure 4: Elevation And Side View Of No. 3 Pier (Unit: Cm)

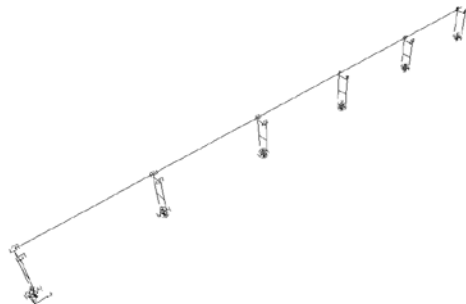


Figure 5: The Finite Element Model Of The Whole Bridge

(a) Model 1: No. 4 pier of this model is fixed while the others are mobile. All the piers are fixed with pot rubber bearings. The ship will hit the abutment of No. 3 pier. The longitudinal friction of bearing should be considered. Model 1 is shown as in Figure 6.

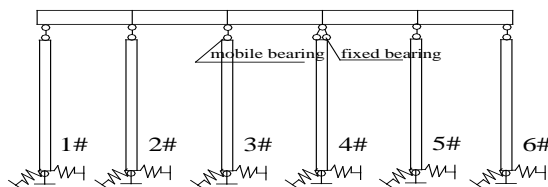


Figure 6: Calculation Diagram Of Model 1

(b) Model 2: The bearings in this model are all lead rubber, and the ship will hit the abutment of No. 3 pier.

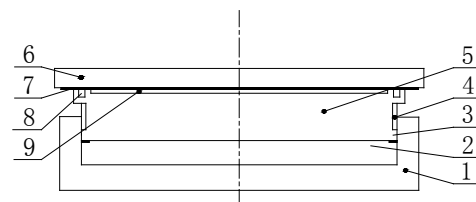
(c) Model 3: The bearings in this model are all hyperboloid spheroid, and the ship will also hit the abutment of No. 3 pier.

### 3.3 The Three Different Bearing Types And Their Stimulation Parameters

The bridge bearing is an important part joining the upper and lower structure of a bridge, which has been proven by large amount of experiment analysis. The dynamic characteristic of the bearing has great influence on the dynamic responses of the bridge structure. Many scholars both home and abroad have conducted a series studies on the characteristics and calculation modes of different types of bearings[6-9]. There are many types of bridge bearings, and the followings types are widely used in projects: plate rubber bearing, polytetrafluoroethylene (PTFE) sliding bearing, pot rubber bearing, seismic resistance pot rubber bearing, hyperboloid bearing, lead rubber bearing, spheroid bearing and arch steel plate bearing[10], etc.. This article mainly studies the influences that the three different bearings, namely, pot rubber bearing, hyperboloid bearing and lead rubber bearing, have on the responses of the key structures of a continuous bridge under a collision.

#### 3.3.1 Pot rubber bearing and its stimulation parameters

The ordinary rubber bearing is shown in Figure 7, whose mechanical property is linear elasticity. The relative displacement between the upper and lower structure of the bridge is realized through the ultralow friction coefficient between the PTFE plate and the steel plate. It is mainly characterized by low damping. And large bearing displacement may be produced even under low horizontal loading.



1 the lower bearing plate 2 pressure-bearing rubber plate 3 brass tight loop 4 seal ring I 5 middle steelscaleboard 6 the upper bearing plate 7 middle sliding board 8 seal ring II 9 PTFE board

Figure 7: Ordinary Rubber Bearing

Horizontal nonlinear spring is used in the stimulation. The pot bearing on the hit pier is transversely fixed and the longitudinal part is stimulated with elastic plasticity plastic unit with the horizontal rigidity 51740KN/m. The post-yield rigidity is fixed as 1/10000 of the pre-yield

rigidity and the smooth value is 10 so as to guarantee iteration convergence.

### 3.3.2 Lead rubber bearing and its parameters

The lead rubber bearing is a kind of shock resistant bearing with lead stick put into the ordinary rubber bearing to improve its hysteretic energy capability. The lead rubber bearing not only meets the rigidity requirements of static load, but also provides the yield rigidity required by earthquake load. Under a relatively high earthquake load, the lead rubber bearing is barely affected by horizontal loading with its excellent hysteretic characteristics. It can consume large amount of vibrational energy and restore its force with the function of the rubber. The hysteretic curve area of the lead rubber bearing is much bigger than that of ordinary rubber bearings, and its initial rigidity is ten times as much as that of ordinary rubber bearings, and its post-yield rigidity is close to the shearing rigidity of ordinary rubber bearings.

The great many power performance experiment have proven that the hysteretic curve of lead rubber bearings is bilinear, therefore, the following bilinear resilience model is used for the earthquake response analysis of lead rubber bearings. In Fig. 8, K refers to the rigidity on elastic stage,  $x_y$  is yield displacement,  $K_p$  is the rigidity on plastic stage,  $X_o$  is the point of speed changing symbol, and  $Q_y = Kx_y$  is the yield shearing force.

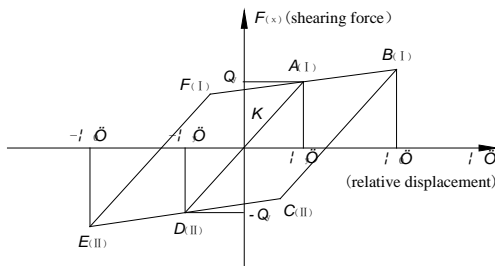


Figure 8: The Bilinear Resilience Model

The yield force of the lead rubber bearing in this article is 561kN, the initial rigidity is 30100kN/m, and the yield rate (the rate between the initial yield rigidity and post-yield rigidity) is 0.1528.

### 3.3.3 Hyperboloid bearing and its stimulation parameters

Hyperboloid bearing belongs to the category of sliding bearing and is composed of upper bearing plate with a sliding spherical surface, a bispherical middle bearing plate, a lower bearing plate with rotating spherical surface and a ring cuff, as is shown in Fig. 9. When the structure receives

relatively low ground drive, the ring cuff's constraint on the upper and lower plates prevents the upper structure from sliding and thus keeps the structure stable; while the drive exceeds the limit, the bolt joining the ring cuff and the upper bearing plate will be cut and sliding will happen. At this point, the force transmitted to the upper structure will not increase with the ground drive.

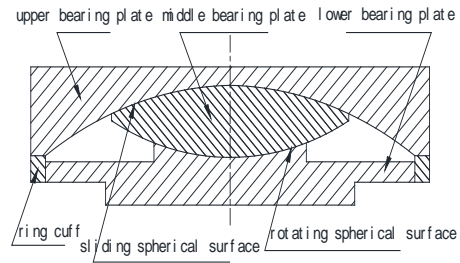


Figure 9: Hyperboloid Spheroid Bearing

The hysteretic curve of hyperboloid spheroid bearing resembles the stress-strain relationship of elastic-perfectly plastic material, and the resilience model used in this article is shown as follows. In Fig. 10,  $F_x$  refers to the critical friction force,  $x$  refers to the relative displacement of the upper structure and the pier top, and  $x_y$  is critical displacement with the limit from 0.002 to 0.005 meter. According to the condition that the maximum value of elastic restoring force equal to the critical sliding friction force, the critical displacement value  $x_y = \frac{u_d R}{k}$ , in which  $u_d$  refers to the sliding friction coefficient, which is usually 0.02, and  $R$  refers to the gravity that the upper structure has on the bearing (kN).

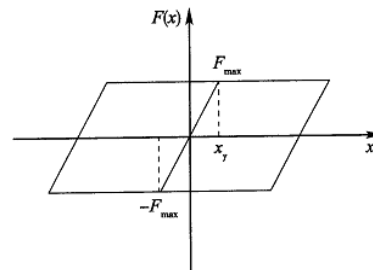


Figure 10: Resilience Model Of The Sliding Bearing

The support reaction to dead load of the hyperboloid spheroid seismic isolation bearing  $W=6700kN$ , the friction coefficient  $u=0.02$ , the radius of the bearing curvature  $R=4m$ , pre-displacement rigidity is 45000kN/m, the yield force is 134kN and the ratio of the post-yield rigidity to elastic rigidity is 0.02.

### 3.4 Calculation And Result Analysis Of Bridge Dynamic Response

The mechanism of ship-bridge collision is very complicated, and the slight difference of collision position or the collision angle may lead to a quite different result[15]. The collision angle refers to the included angle between the ship axis and the transverse direction of bridge pier. The finite-element ship model hits the above three continuous bridge models at the constant speed of 4m/s with different angles of 0°, 2°, 4° till 50°. According to the simplified analysis and numerical stimulation calculation analysis, we can get the collision force time-history of the ship under collision. Put it as the

input load into the bridge calculation model built with SAP2000 to analyze whole bridge dynamic response, and we will get the different responses of the key structure of the continuous bridges with the above three different bearings with different collision angles. The key structure includes the maximum abutment displacement, maximum pier top displacement, maximum bearing shearing force, maximum pier bottom shearing force and moment area, maximum pile top shearing force and moment area, etc. The curves of the response are shown as follows in Figure11-18.

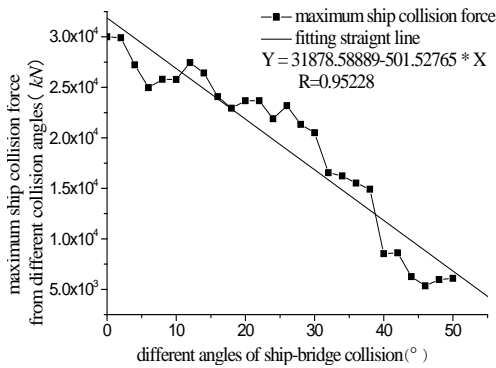


Figure 11: The Maximum Ship Collision Force With Different Angles

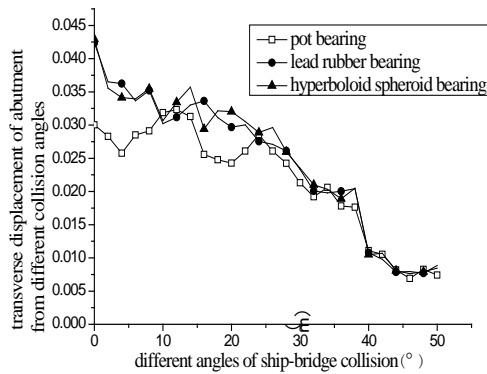


Figure 12: The Maximum Transverse Displacement Of Pile Cap With Different Angles

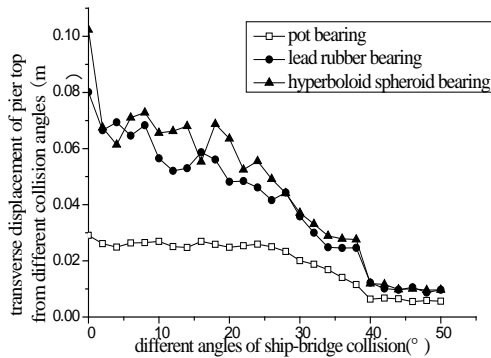


Figure 13: The Maximum Transverse Displacement Of The Pile Top With Different Angles

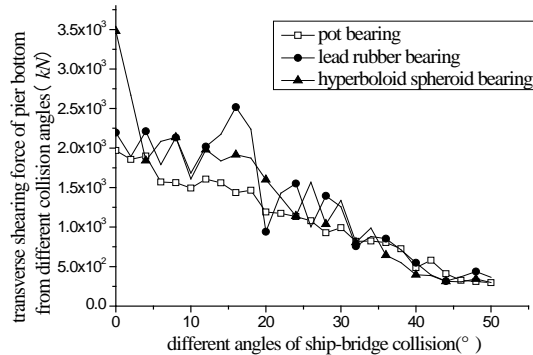


Figure 14: The Maximum Transverse Shear Force Of Pier Bottom With Different Angles

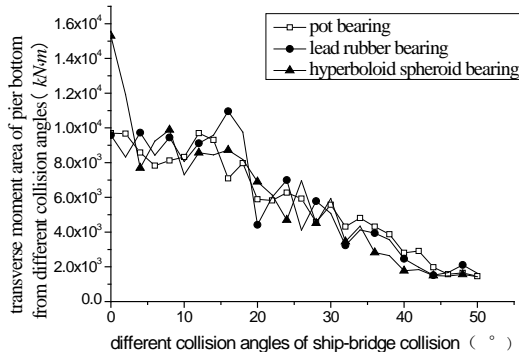


Figure 15: The Maximum Transverse Bending Moment Of Pier Bottom With Different Angles

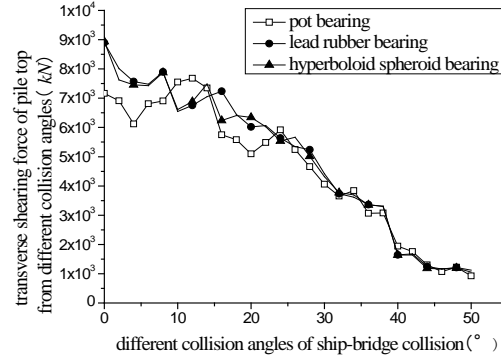


Figure 16: The Maximum Transverse Shear Force Of Pile Bottom With Different Angles

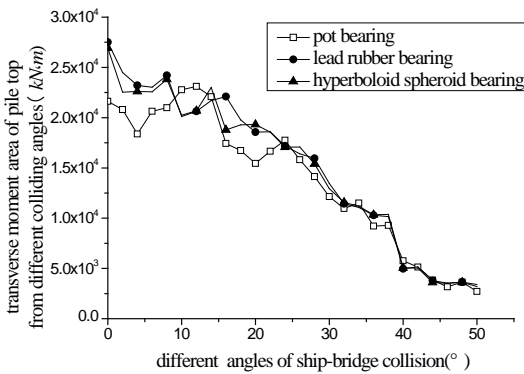


Figure 17: The Maximum Longitudinal Bending Moment Of Pile Bottom With Different Angles

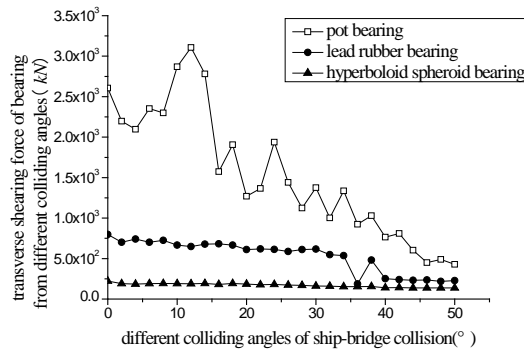


Figure 18: The Maximum Transverse Shear Force Of Bearing With Different Angles

The calculation result indicates that the maximum collision force drops with the increase of the colliding angle. But the responses of bridge key structures do not decrease with the increase of the colliding angle. And there is a large difference among the responses of the bridges with three different bearings. The changing rules are summarized as follows:

(1) From Figure11, with the increase of the collision angle, the maximum ship collision force decreased linearly, while the responses of the key bridge structures do not decrease with it. From Figure12, when the transverse abutment displacement response of continuous bridge with the pot bearing reaches the maximum value under the 10° collision angle, the curve around 25° has a slight rally and then show a oscillation decrease tendency. The curve of the maximum abutment transverse displacement of the bridges with lead bearing and hyperboloid spheroid bearing are on a stable declining tendency and without obvious fluctuation, the maximum value will appear in the 0° collision angle. The transverse rigidity of the pot bearing is far greater than that of the lead bearing and hyperboloid spheroid bearing, so it joins the girder and the lower part much tighter and makes

the piers as a whole resist together against the collision force. When 0° ship-bridge collision happens, the ship hits against the bridge which is much heavier and will produce a large deformation while the abutment produces a slight deformation. When the transverse rigidity of the bearing is small, yielding happens to the lead bearing, which leads to the sliding of the upper structure and the increasing of the abutment displacement and thus the deformation of the collision ship bow is small.

(2) From Figure14 and Figure15, with the increase of the collision angle, the maximum shearing force of pier bottom of pot bearing bridge is less likely to fluctuate and is more stable. If the angle is less than 10° in a collision against the lead bearing bridge, with the increase of the colliding angle, the maximum transverse shearing force of the pier bottom is in the trend of gradual decrease and it will witness obvious fluctuation at about 15°, and it will gradually decrease after that. The maximum transverse shearing force of pier bottom of the hyperboloid spheroid bearing bridge rapidly decrease with the increase of the angle within the limit of no more than five degree. The absolute value of the slope is very large and then in is the trend of gradual decrease. The response of the

transverse shearing force of the pier bottom of hyperboloid spheroid bearing bridge is the largest.

From the above three conditions, it can be found that the transverse yielding rigidity of hyperboloid spheroid bearing is small since the bridge is small-spanned. When collision happens at  $0^\circ$ , the maximum transverse shearing force of pier bottom of hyperboloid spheroid bearing bridge is 3480KN, 4% less than the response value 3635KN when the ship hits a single pier. This explains that when the pier yielding rigidity is small, and the joining rigidity of the lower and upper part is low, the vibration of the upper part on the pier is not big under a ship collision, which can be regarded as the action between the single pier and the ship. When the bearing rigidity of, for example, a pot bearing, is large, that is to say, the upper and lower parts are tightly connected, the upper structure changes the basic vibrating frequency of the pier shaft and the boundary conditions, and reduces the responses of the pier stud under the ship collision force. It is also found that the bigger the transverse rigidity of the bearing, the smoother the curve, and the smaller the transverse rigidity, the more obvious the curve fluctuation.

(3) From Figure16 and Figure17, with the increase of the colliding angle, the maximum transverse shearing force of the pier top of pot bearing bridge does not on monotone decrease, and its variation tendency resembles that of the transverse moment area of pier tops. If collision happens within the angle from  $10^\circ$  to  $15^\circ$ , the piles are very likely to be damaged by shearing force. The maximum transverse shearing force of the pier top of the lead bearing bridge is on smooth decrease and without evident fluctuation. The maximum appears when the collision happens from the angle of zero degree, and the shearing force stays strong and the pile foundation is in danger when the colliding angle is within  $15^\circ$ . The response curves of hyperboloid spheroid bearing bridge and lead bearing bridge are highly similar. Since the transverse rigidity of the pot bearing is high, the collision force transmits both upward to the upper structure and downward to the pile foundation. But with the quake insulation bearing, the collision force is mostly transmitted to the pile foundation, and leads to obvious responses from the pile foundations of lead bearing bridge and hyperboloid spheroid bearing bridge.

From the above three conditions, it is found that the response to the collision is the smallest with the pot bearing bridge. When the upper part and the

lower part is tightly connected, the full bridge structure reacts with the ship, and the ship is damaged while the bridge responses slightly. The type of the bearings has much weaker influence on the pile response than on the piers.

(4) From Figure18, with the increase of the collision angle, the maximum transverse shearing force of pot bearing is not on monotone decrease, but abruptly increases at the angle between  $10^\circ$  to  $15^\circ$  and gradually decreases after that. When the angle is between  $10^\circ$  and  $15^\circ$ , the bearings are easy to damage. With the increase of the collision angle, the maximum transverse shearing force of the lead bearing decreases gradually and the absolute value of the slope will be very small. The response value of the transverse shearing force of hyperboloid spheroid bearing is the smallest. The transverse shearing force of pot bearing is much bigger than that of the lead bearing and the hyperboloid bearing.

#### 4. CONCLUSION

(1) In this article, a simplified method of ship-bridge collision is proposed. The time-history of the collision force under ship-rigid wall collision, as the dynamic load, is put into the finite-element model of the bridge. Then the influence of the bearing types on the responses of the key bridge structures is studied to prove the feasibility of the simplified method.

(2) The responses of the key bridge structures with three different bearings are compared and analyzed. It is found that the responses of the key structures of the pot bearing continuous bridge are the smallest. That is to say, when the upper part and lower part are tightly connected, all the bridge piers as a whole resist together against the collision force and the key structures of the bridge respond slightly.

(3) Pot bearing joins the girder and the lower part much tighter. The upper structure changes vibrational frequency of the pier and boundary conditions, which decrease the responses of pile and pier. With regard to the isolation bearings, the upper structures have slight influence on the modes of substructures. When the yield strength of bearings is small, it can be regarded as the collision between the pier and ship. On the other hand, the isolation bearings make the collision force barely transmit to the upper part, but only to the pile foundation, which makes the responses of the pile foundation larger. The influence of the bearing type on the



response of the piles is much weaker than that of the piers.

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