

EFFECT OF VEHICLE QUALITY AND SPEED ON THE IMPACT CHARACTERISTICS OF AN OVERPASS BRIDGE PIER

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ABSTRACT

To study the impact of the mechanical characteristics of heavy trucks on piers under different masses and speeds, a new equivalent simplified model of heavy trucks is proposed in this paper. The reliability of the calculation model is verified by studying the pier of the G1011 Ha-Tong high-speed K302+095 separated overpass, which was subjected to impact by a heavy truck. A finite element model of a heavy truck and a pier is established using the finite element software ABAQUS, and the influence of heavy truck load and impact speed on the impact force and pier stress is analysed. Results show that the peak of impact force increases with the increase in the mass and impact speed of heavy trucks. The high-stress area of the pier is concentrated in the root and the impact position, and an inclined through-crack is formed at 45° with the pier axis. The results also reveal the influence law of the quality of heavy trucks and impact speed on the impact force and stress of the pier and provide a new theoretical basis for the anti-collision design of piers and the limitation of current specifications on the high-speed impact of heavy trucks on piers.

KEYWORDS

Heavy truck load, Impact speed, Pier impact, Finite element analysis, Impact force

INTRODUCTION

Accidents caused by vehicle impacts on piers have increased with the increase in the number of overpass bridges and motor vehicle carrying capacity, thereby not only causing loss of life and property but also threatening the safe operation of bridges. Highway accidents are likely to result in pier collapse due to the large number of heavy vehicles and high speed. Thus, relevant departments, engineers and scholars have conducted research on pier anti-collision of vehicles [1].

At present, local and foreign research on vehicle–pier impact mainly focuses on the impact force and dynamic response of piers, and research methods include experimental research and numerical simulation [2-8]. Popp was the first to test truck impact on a column structure, and a truck impact test was conducted on concrete and steel columns [9]. A simplified vehicle–pier model is typically used in experimental studies because of the high cost of impact test of large vehicles. Zhu Yadi and Lu Wenliang conducted a model impact test of a truck and a pier and found that impact force has a linear relationship with truck speed; in addition, the impact force is related to the diameter and slenderness-to-length ratio of the pier [10]. With the development of a large general finite element software and the progress of engineering simulation technology, numerical simulation has become an important research method for studying vehicle–bridge collisions. El-tawil et al. first established the fine finite element model to perform a numerical simulation analysis of car impact on bridge piers, and research shows that under some special conditions, the

provisions of the 1998 U.S. Bridge Design Code have unsafe characteristics [11]. Agrawal et al. analysed the impact behaviour between a truck and a reinforced concrete pier by means of numerical simulation and proposed a design method based on impact resistance [12]. Lu Wenliang used LS-DYNA to establish the finite element model of vehicle-pier-column collision, and analysed the dynamic response of the pier when the vehicle hit the pier without velocity. The calculation results show that the dynamic response of the pier column is basically proportional to the speed of the vehicle [13]. Xu Linfeng used ANSYS/LS-DYNA finite element analysis software to study the influence of vehicle impact speed and mass on the impact force time history curve [14]. On the basis of the experiment, Liu Shan established the finite element model of the real car impact on the pier with LS-DYNA, and calculated and analysed the impact force and the damage of the concrete pier. The results show that the impact force is proportional to the mass and speed of the vehicle, after the frame pier and the single column pier are hit by the vehicle, the damage position is mainly the root area of the pier (bending failure) and the impact point area (local failure) [15].

The collision of a truck into a bridge pier will cause damage to the bridge, reduce its bearing capacity and seismic resistance and even cause the bridge to collapse. At present, the relevant research is still in its infancy, and no reliable simplified analysis method is available for heavy vehicles impacting bridge piers. Existing specifications can solve the impact problem of small mass and low speed, but they are unsuitable for high-speed impact of heavy vehicles on bridge piers. The influencing factors and related mechanisms of heavy vehicles impacting bridge piers have not been fully studied.

Considering the high-test cost and the mature development of numerical simulation technology, this paper adopts the general finite element software ABAQUS to analyse the influencing factors of heavy trucks impacting bridge piers. On the basis of the Ha-Tong high-speed accident, a new equivalent model of heavy truck is proposed, and a finite element model of a heavy truck impacting a rectangular reinforced concrete pier is established. The reliability of the numerical simulation results is verified. On the basis of the impact course of the truck, the damage characteristics of the pier hit by heavy vehicles are analysed. The effects of the quality and impact speed of the truck on the impact force of the pier and the von Mises stress are revealed. This paper provides a new theoretical basis for the anti-collision design of piers and the limitation of current specifications in the high-speed impact of heavy trucks on piers.

ESTABLISHMENT OF THE FINITE ELEMENT MODEL

Establishment of the finite element model of the pier

Rectangular-reinforced concrete section is adopted for the pier of the G1011 Ha-Tong high-speed K302+095 separated overpass, which is 1200 mm long, 200 mm wide and 4850 mm high. The diameter of the main reinforcement is 25 mm, the diameter of the stirrup is 8 mm and the strength grade of the concrete is C25.

ABAQUS was used to establish the numerical analysis model. The concrete element C3D8R was used for the pier, and the T3D2 truss element was used for the pier rebar. The concrete plastic damage model is adopted, the paper assumes that the initial strain of undamaged concrete is 0 and its material parameters are shown in Table 1. The rebar adopts the ideal elastic-plastic constitutive model, and its material parameters are shown in Table 2. According to the real bridge collision accident case, when the pier is hit by a car, the lateral displacement of the top of the pier causes the support to fall off, whereas the foundation does not change. Thus, the finite element model boundary condition of the pier features consolidation at the bottom of the foundation and a free top area.

Tab. 1 - C25 plastic constitutive parameters of concrete

Tensile plasticity									
Stress (MPa)	1.780	1.457	1.113	0.800	0.536	0.359	0.161	0.073	0.040
Strain ($\times 10^{-2}$)	0.00	0.01	0.03	0.05	0.08	0.10	0.20	0.30	0.50
Compression plasticity									
Stress (MPa)	24.019	29.208	31.709	32.358	31.768	30.379	21.907	14.897	2.953
Strain ($\times 10^{-2}$)	0.00	0.04	0.08	0.12	0.16	0.20	0.36	0.50	1.00

Tab. 2 - Constitutive parameters of steel bars

Elastic modulus E (Pa)	Poisson's ratio μ	Yield strength σ_y (Pa)	Density (kg/m ³)
1.9×10^{11}	0.3	2.1×10^8	7800

Establishment of the finite element model of the heavy truck

With a heavy truck as the research object, combined with the advantages of the fine finite element model and the simplified finite element model, this paper, considering the impact effect of a heavy vehicle, proposes the equivalent truck finite element model to mainly simulate the five components that have the greatest influence on pier impact. These five components are the front, carriage, chassis steel frame, engine and cargo; other components of the truck are ignored. The equivalent model of heavy trucks is shown in Figure 1. The S4R shell unit is used for the locomotive and carriage, and the C3D8R solid unit is used for the engine, truck chassis and cargo. Based on heavy vehicle structure, the size of the engine block is determined to be 300 mm \times 500 mm \times 700 mm. the size of the truck chassis is determined to be 300 mm \times 230mm \times 2500 mm. Q345 steel is used for vehicle models, whose material parameters are shown in Table 3.

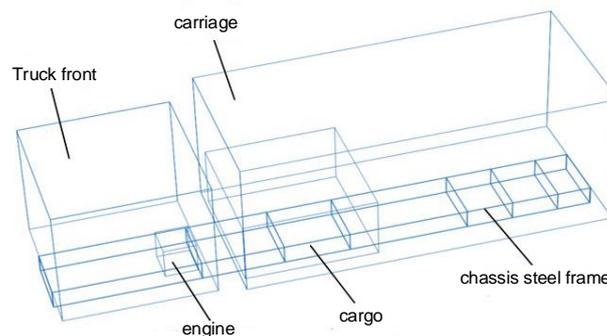


Fig.1 - Equivalent model of heavy truck

Tab. 3 - Constitutive parameters of the Q345 steel

Elastic modulus E (Pa)	Poisson's ratio μ	Yield strength σ_y (Pa)	Density (kg/m ³)
2.06×10^{11}	0.3	3.45×10^8	7800

This section should describe in detail the study material, procedures and methods used.

VERIFICATION OF THE FINITE ELEMENT MODEL

Figure 2 shows the damage characteristics of the pier of the G1011 Ha-Tong high-speed K302+095 separated overpass after a 36t heavy truck collided into the pier. The concrete on the pier's failure surface fell down, showing a gap of about 10 cm. The exposed steel bar underwent plastic deformation. The failure surface between the impact point and the pier base presented a diagonal failure form of about 45° with the pier axis. To verify the reliability of the finite element model, Figure 3 shows a von Mises stress cloud diagram of the impact of an equivalent truck model on bridge piers with $m = 36t$ and $v = 80$ km/h. Figure 3 shows the position of the impact and the maximum stress of the pier on the base of the pier. The area with large stress is mainly distributed between the base and the impact position, and the failure surface beyond the tensile strength of concrete is about 45° from the pier axis. A comparison between the numerical simulation results and actual collision accidents shows that the damage characteristics of the piers are consistent. This result indicates that collisions between heavy trucks and piers can be well simulated by using the equivalent model of heavy truck.



Fig. 2 - Damage characteristics of the pier of the G1011 Ha-Tong high-speed K302+095 separated overpass

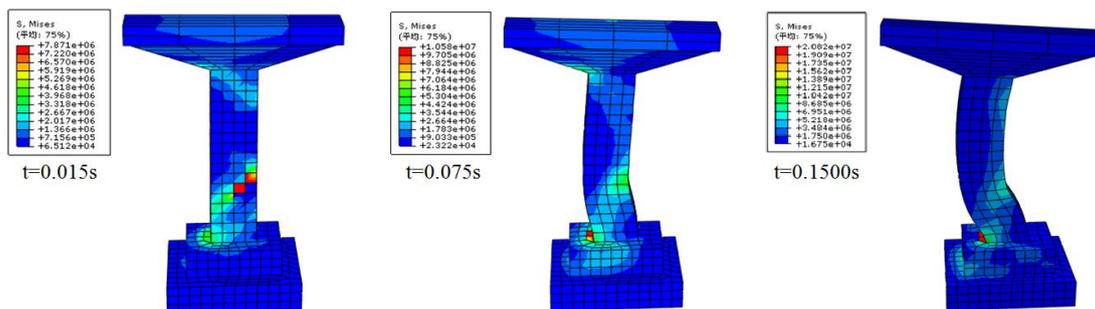


Fig. 3 - Von Mises stress cloud diagram of piers under truck impact

ANALYSIS OF THE RESULTS AND DISCUSSION

Analysis of impact force

Figure 4 presents the time–history curve of the impact force of trucks with a mass of 20 t at different impact speeds on the basis of the velocity 60–120 km/h driving range of cars as indicated by the provisions of the expressway. As shown in the figure, the peak impact force in the curve represents the maximum contact force between the anti-collision beam and the pier, the maximum impact force between the engine and the pier, the maximum contact reaction force borne by the cargo in the carriage and the peak impact force generated by the coupling vibration of the cargo and the locomotive in the late stage.

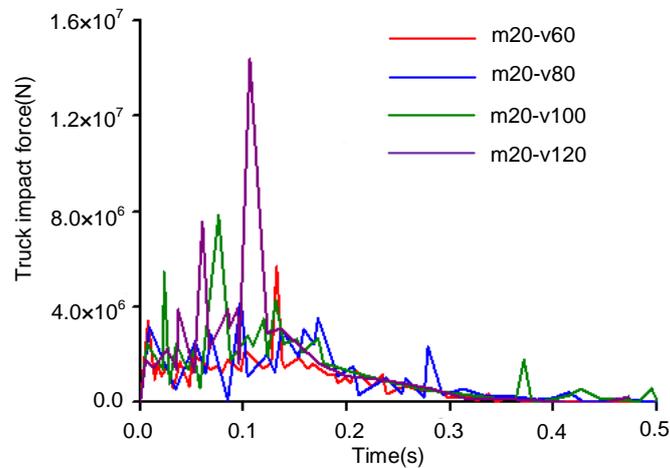


Fig.4 - Time-history curve of truck impact force with a mass of 20t

To clearly show the peak impact force and its corresponding time, Figure 5(a) displays the corresponding time of the peak impact force at different parts of a truck with a mass of 20t at different impact speeds. As shown in the Figure 5(a), the impact process of trucks and piers is different under different impact speeds. In the low-speed impact condition (m20t-v60m/s), only the anti-collision beam and the engine have collision contact, and the cargo has no collision contact. The reason for this situation is that the impact speed of the truck is relatively small, the locomotive consumes a great amount of kinetic energy during the impact process and no hard contact with the cargo occurs to produce the peak impact force. As the impact speed increases (m20t-v80m/s, m20t-v100m/s and m20t-v120m/s), the truck's kinetic energy increases and the cargo makes impact contact in addition to the collision beam and engine. Moreover, the time of collision contact between truck parts is early.

Figure 5(b) shows the impact force peaks at different parts of a truck with a mass of 20t at different impact speeds. At low-speed impact, the peak impact force of the engine is the largest among all the components. With the increase in impact speed, the peak impact force of the cargo increases gradually and gradually exceeds the peak impact force of the engine. In addition, as the impact speed increases, the peak impact force produced by the truck's engine increases when it hits the pier. Under the impact speed of 80 km/h, the variation trend of the peak impact force has different results due to the complexity of the truck's internal structure. Under certain impact speeds, the front and the pier will consume a great amount of energy due to coupling vibration before impact contact.

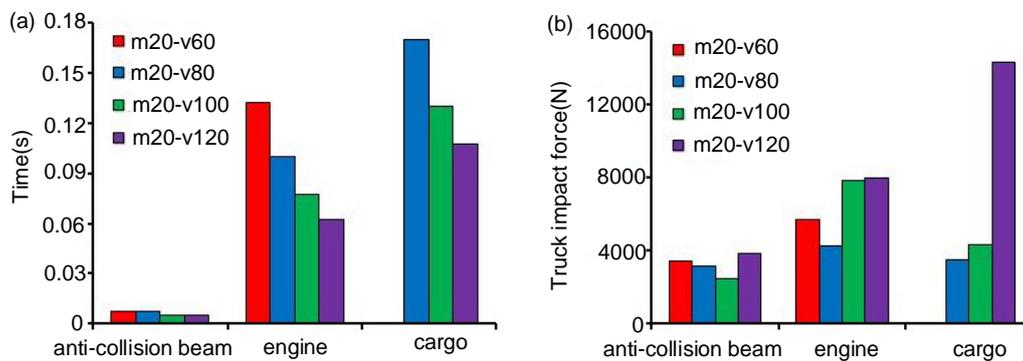


Fig. 5 (a) - Time corresponding to the peak impact force of each part of the truck; (b) Peak impact force of each part of the truck

Figure 6 shows the time–history curves of the impact forces of trucks with different masses at the impact speed of 80 km/h. The mass of the truck was changed by changing the material density of the cargo.

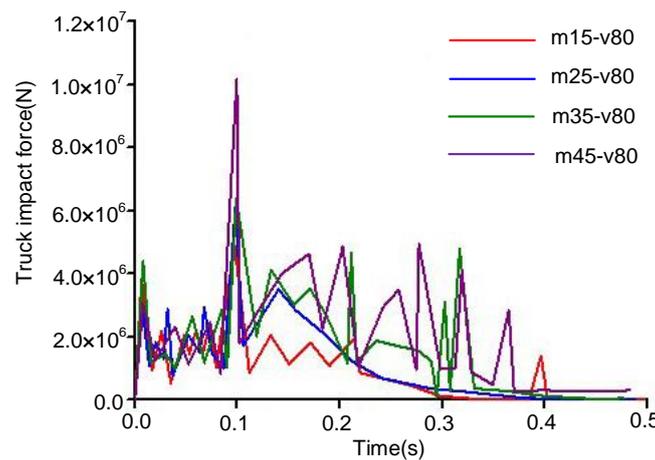


Fig. 6 - Time–history curve of impact force of truck with a speed of 80 km/h

As shown in the Figure 6, the duration of the impact process is approximately 0.4 s. When the truck has a small mass, the impact energy consumption mainly occurs in the front. With the increase in the mass of the cargo, the peak of the impact force increases during collision. This phenomenon is due to the coupling vibration effect of the steel frame of the truck body after the collision between the compressed front and the cargo.

Figure 7 shows the impact force peaks and the corresponding time of different parts of trucks with different masses under impact speed of 80 km/h.

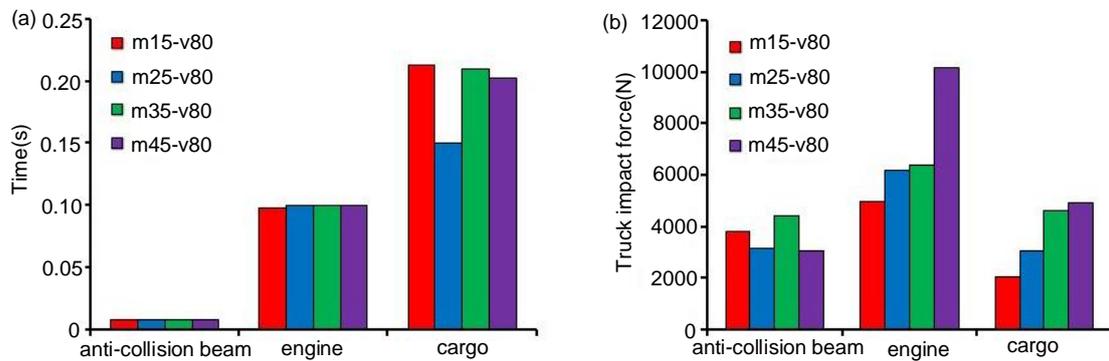


Fig. 7 (a) - Time corresponding to the peak impact force of each part of the truck; (b) peak impact force of each part of the truck

As shown in the Figure 7, under a certain impact speed, the time of peak impact force generated by the collision of anti-collision beams and engines of trucks of different masses remains unchanged. The time of peak impact force due to the impact of the cargo varies with mass. In addition, with the increase in the truck mass, the peak impact force increases, and the maximum peak impact force is generated by the impact with the engine.

Stress analysis

The stress response of each part is an important basis for judging the damage degree of the pier and its anti-collision design when it is hit by vehicles. Figure 8 shows the von Mises stress distribution cloud diagram of the pier hit by a truck with a mass of 20 t under different impact speeds at the moment of impact force peak of all components. As shown in the Figure 8(a)~(d), when the collision peak of the anti-collision beam of the truck occurs, the von Mises stress distribution of the piers extends to the top and bottom at a 45° angle along the front contact surface. This result indicates that when the anti-collision beam of the truck contacts the piers, local damage and cracks will occur in the concrete. During continuous compression deformation of the anti-collision beam, front shell and chassis steel frame, the stress at the top of the pier column decreases and that at the bottom of the pier column increases. The maximum stress occurs at the back of the pier's impact point, the junction of the pier and the foundation. When the engine begins to undergo impact contact, the stress is mainly concentrated near the impact point of the truck chassis and the base of the bridge pier. At this time, the impact point and the base of the bridge pier are seriously damaged. As the impact proceeds, the von Mises stress distribution of the piers does not change significantly at the cargo impact stage. However, with the increase in the truck impact speed, the deformation of the piers increases. In addition, the impact position of the piers and the high stress distribution area of the pier base increase, forming a 45° through-crack to promote the development of cracks. In addition, the Figure 8 shows that the high-stress area is concentrated at the collision position and the base of the pier.

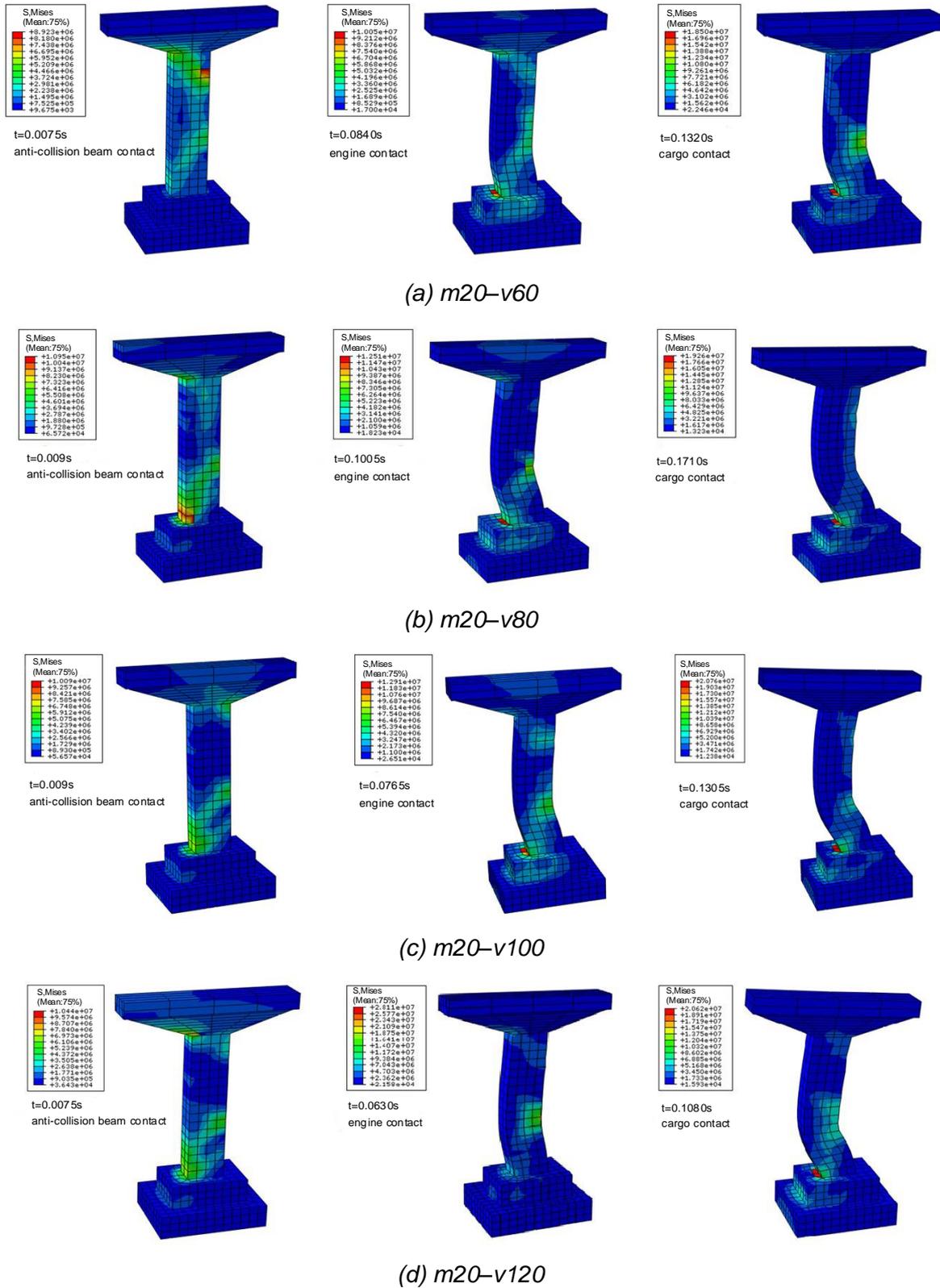


Fig. 8 - Von Mises stress cloud diagram of piers under different impact speeds

Figure 9 shows the von Mises equivalent stress time–history curve of a truck with a mass of 20t at different impact speeds. As shown in the Figure 9, the stress of the truck increases rapidly at the beginning of contact with the pier and then decreases after reaching a peak value as a result of the collision between the anti-collision beam of the truck and the pier. With the compression deformation of the front, the stress continues to increase and reaches the maximum value of the impact process. As the energy dissipates, the stress decreases and remains at a low level. In addition, the Figure 9 shows no obvious change in the maximum von Mises stress with the increase in the truck impact speed, but the time point at which the maximum stress is produced is different. Moreover, the maximum von Mises stress on the impact position of the pier is higher than that on the base of the pier.

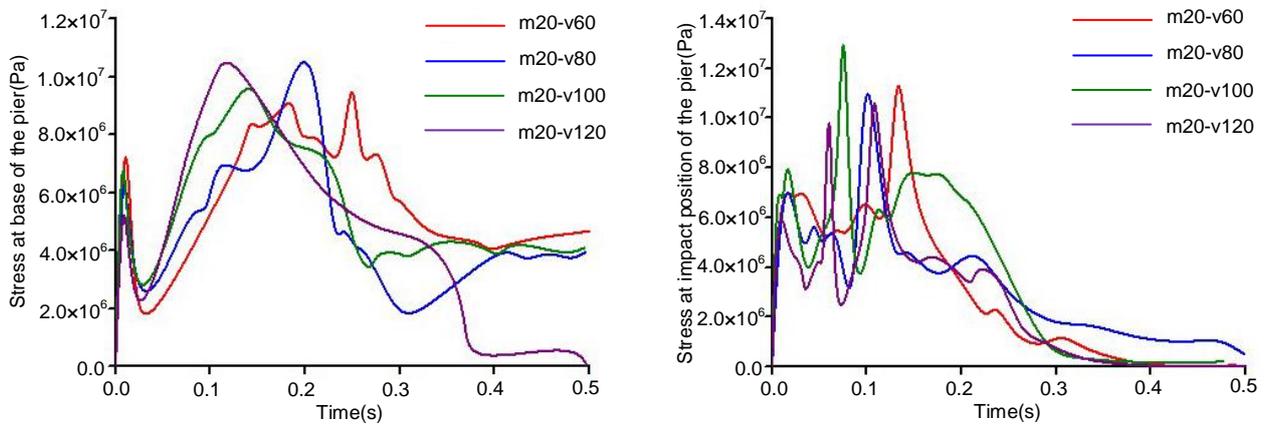


Fig. 9 - Time–history curves of the von Mises stress of impact position and the base of the pier at different impact speeds

Figure 10 shows the peak impact force moment of each part of the trucks with different masses at the impact speed of 80 km/h and the von Mises stress distribution of the pier. As shown in the Figure 10(a)~(d), when the anti-collision beam initially impacts the pier, the pier column does not deform. However, the impact of the pier generates stress, which then spreads to both ends to form a strip stress area, and the strip has a 45° angle with the axis of the column. With the compression process of impact, the engine will collide with the bridge, and the pier will show deformation characteristics. The maximum von Mises stress distribution will be located around the impact position and the base of the pier. When the cargo collides with the bridge, the pier deforms further. In addition, the high-stress areas of the impact position and the base of the pier expand and become a whole, forming through-cracks.

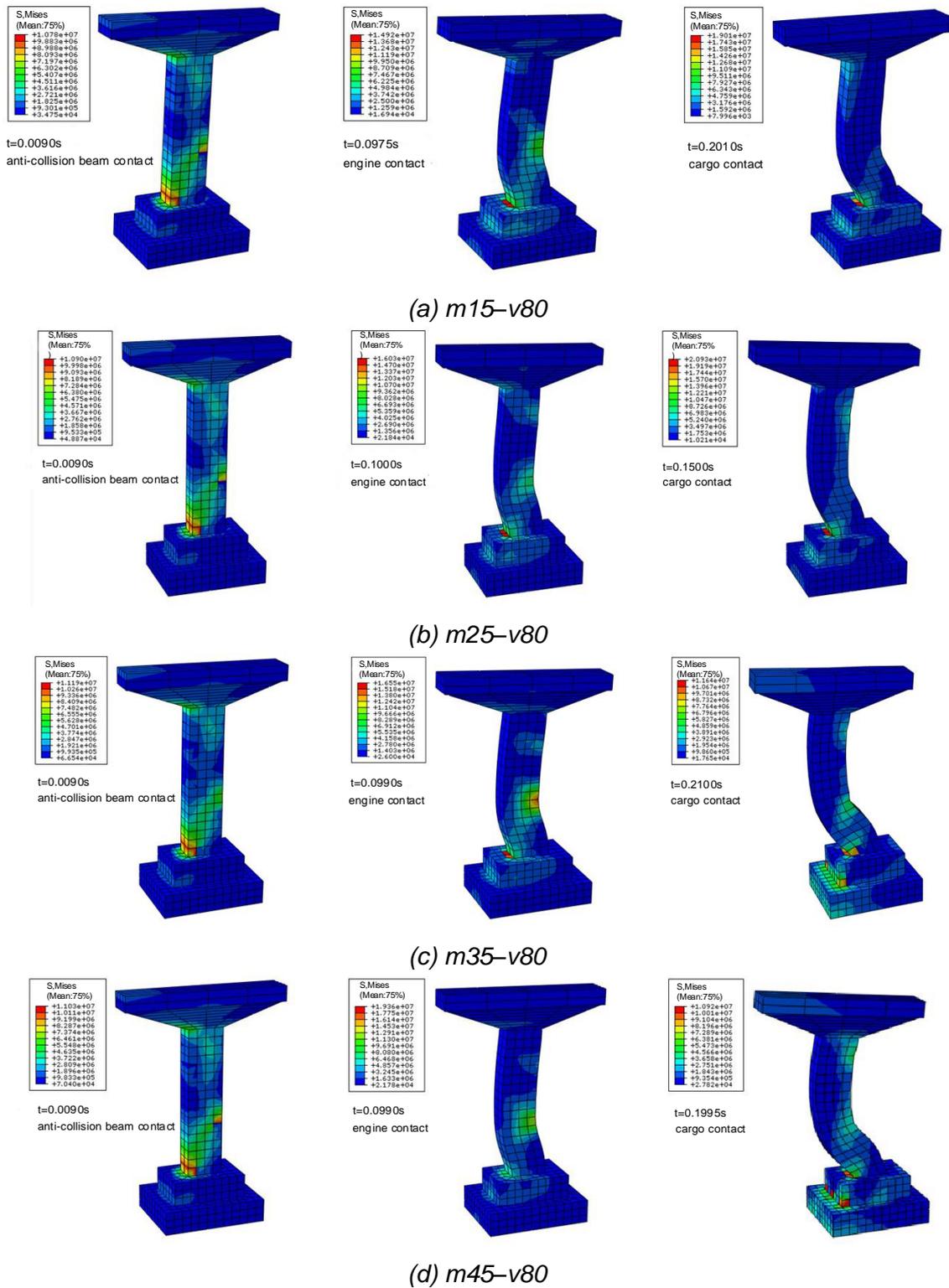


Fig. 10 - Von Mises stress cloud image of the piers impacted by trucks with different masses

Figure 11 shows the time–history curves of the von Mises equivalent stress at the impact position and base of piers with different masses of trucks at the impact speed of 80 km/h. As shown in the Figure 11, the stress increases rapidly at the initial moment when the truck and the

pier experience impact and then decreases after reaching the peak, forming a triangular pulse as a result of the collision of anti-collision beams and piers. With the compression deformation of the front, the stress at the base of the piers increases and reaches the maximum during the impact process. The stress at the pier's impact point remains at a high level and reaches the maximum stress value during the impact process after the shock. As the energy dissipates, the stress begins to decrease and eventually remains at a low level. In addition, with the increase in the truck mass, the maximum von Mises stress at the pier base does not change significantly because the deformation at the base of the pier causes the material to reach its strength limit, the stress of the pier is released after failure.

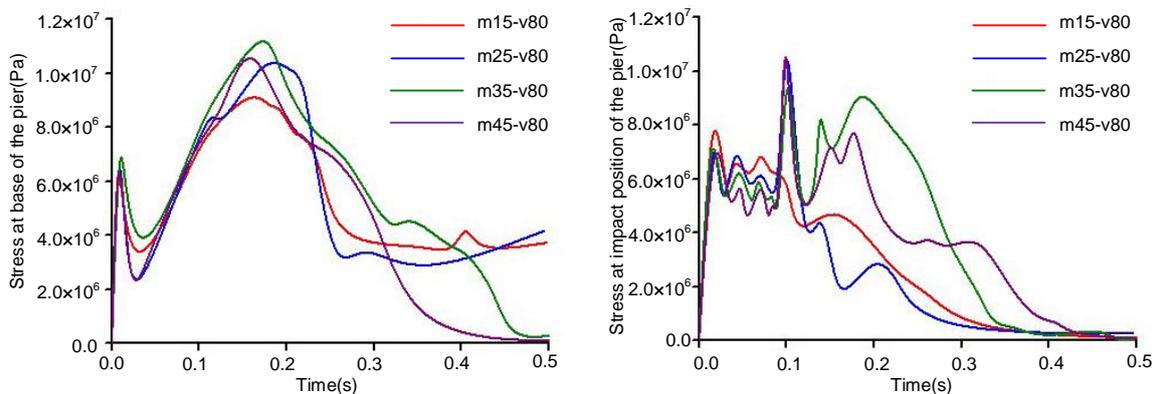


Fig. 11 - Von Mises stress time–history curves of the impact of trucks with different masses on the base and the impact point of the piers

CONCLUSION

In this paper, an equivalent truck finite element model is developed on the basis of the numerical simulation method to analyse the collision between heavy trucks and piers. This model combines the advantages of the fine finite element model and the simplified finite element model and considers the impact effect of heavy vehicles. The results show that with the increase in mass and impact speed, the kinetic energy of the truck and the peak impact force increase. The von Mises stress at the base and impact position of the piers is large. In addition, with the increase in truck mass and impact speed, the deformation of the pier increases and the stress areas are connected as a whole, thereby forming an oblique through-crack with a 45° angle to the axis of the pier column.

In sum, the equivalent truck finite element model is developed, taking the main structural components of trucks into account. In addition, the effects of truck mass and impact speed on the impact force and piers von Mises stress are analysed, thereby providing a new theoretical basis for the limitations of high-speed impact of heavy trucks on piers in anti-collision design and code.

REFERENCES

- [1] Chen Lin.,2015.Research on Bridge Piers Against Vehicle Impact. Hunan University, 2015
- [2] Tsang H, Lam N T K. ,2008.Collapse of Reinforced Concrete Column by Vehicle Impact. Computer-Aided Civil and Infrastructure Engineering, vol. 23: 427-436
- [3] Thilakarathna H M I, Thambiratnam D P, Dhanasekar M et al.,2010. Numerical Simulation of Axially Loaded Concrete Columns under Transverse Impact and Vulnerability Assessment. International Journal of Impact Engineering, vol. 37(11): 1100-1112

- [4] Ferrer B, Ivorra S, Segovia E et al. ,2010. Tridimensional Modelization of the Impact of a Vehicle against a Metallic Parking Column at a Low Speed[J]. Engineering Structures, vol. 32(8): 1986-1992
- [5] Buth C E, Brackin M S, Williams W F et al. ,2011. Collision Loads on Bridge Piers: Phase 2. Report of Guidelines for Designing Bridge Piers and Abutments for Vehicle Collisions. Texas: Texas Transportation Institute Proving Ground:1-87.
- [6] Sharma H, Hurlbauss S, Gardoni P. , 2012. Performance-Based Response Evaluation of Reinforced Concrete Columns Subject to Vehicle Impact. International Journal of Impact Engineering, vol. 43: 52-62
- [7] Joshi A S, Gupta L M. , 2012 A Simulation Study on Quantifying Damage in Bridge Piers Subjected to Vehicle Collisions. International Journal of Advanced Structural Engineering (IJASE), vol. 4(1): 1-13.
- [8] Gomez N, Alipour A., 2014.Study of Circular Reinforced Concrete Bridge Piers Subjected to Vehicular Collisions. Structures Congress 2014, Boston, 577-587.
- [9] Popp C. , 1961. Der Querstoß beim Anprall von Kraftfahrzeugen auf Stützen und Rahmenstiele von Straßenunterführungen. Köln: Stahlbau-Verlag
- [10] Zhu Yadi, Lu wenliang. ,2013.Model tests for collision force between a vehicle and piers, Journal of Vibration and Shock, vol. 32(21): 182-185.
- [11] El-Tawil S, Severino E, Fonseca P., 2005. Vehicle Collision with Bridge Piers. Journal of Bridge Engineering, vol. 10(3): 345-353.
- [12] Agrawal A K, Liu G, Alampalli S., 2013.Effects of Truck Impacts on Bridge Piers. Advanced Materials Research, vol. 639-640: 13-25.
- [13] Lu Wenliang, Li Xiaolong, Peng Boyang,et al.,2012.Analysis of collision dynamic response of vehicle Pier and column Model.Railway Engineering,No.3:12-13+95
- [14] Xu Linfeng.,2014.Research on impact force and strain of bridge pier caused by vehicle collision, dissertation for the degree of master(Beijing Jiaotong University):25-90
- [15] Liu Shan.,2017.Research on impact force of reinforced concrete pier impacted by vehicle, dissertation for the degree of master(Northern University of Technology):9-68