Simulation Analysis of Multi-angle Collision of Super High-Speed Car on Bridge Guardrail

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ABSTRACT

The protective effect of highway guardrails on vehicles is closely related to collision speed and collision angle. With the development of road traffic, it is possible to construct super high-speed highways. When super high-speed vehicles collide with guardrails at different angles, the protective effect of guardrails will vary. In order to analyze the guardrail protection effect during vehicle collision with guardrails, a numerical simulation method was used to model and analyze the guardrail collision process of the super high-speed car, taking into account the impact of different collision angles of the car. The main conclusions are as follows:(1) During the collision of the super high-speed car with guardrails at different angles, the cars did not cross, break through, or ride over the guardrails. The car's wheel tracks were all within the range of the guided exit frame, and the guiding and buffering functions of the guardrail structure met the requirements. As the collision angle between the vehicle and the guardrail continues to increase, the vehicle's wheel track becomes closer to the long side of the guiding exit frame away from the guardrail. As the collision angle increases, the guiding function of the guardrail on the vehicle decreases. (2) As the collision angle between the vehicle and the guardrail increases, the buffering effect of the guardrail on the vehicle decreases, and the risk of passenger injury increases. When the collision angle between the vehicle and the guardrail is 30°, the collision speed and acceleration of the passengers exceed the standard requirements. (3) As the collision angle of vehicles increases, the collision force between cars and guardrails increases, and the collision load acting on the guardrail structure increases. Under larger loads, the deformation of the guardrail structure increases, and the risk of car collision with guardrails increases.

Keywords-Highway guardrails; Protective ability; Numerical simulation; Super high-speed highway

1. INTRODUCTION

The highway serves as a primary conduit for regional economic development, bearing the key responsibility of facilitating road transportation functions. Influenced by factors such as road conditions, driver characteristics, vehicle attributes, and environmental elements, the current maximum speed limit for small vehicles on expressways in our country is set at 120 km/h. With advancements in vehicle technology, the potential for high-speed travel has been enabled. Furthermore, as road technology continues to progress, it will further provide favorable conditions for vehicles to achieve even higher speeds on roadways. However, the design of guardrails currently considers lower vehicle speeds, necessitating further exploration of their protective efficacy for vehicles traveling at exceptionally high speeds.

The protective capabilities of barriers are related to vehicle collision velocity, collision angle, and vehicle weight. In addressing the issue of barrier impact under super high-speed conditions, Bi[1] employed finite element simulation analysis to study the collision process of a maglev train with a concrete barrier, obtaining simulation results on the protective effects of the barrier on the train and the damage to the barrier structure. To meet the energy requirements for roadside barrier collisions on highways, Han[2] conducted emergency evasive maneuvering tests at different vehicle speeds, obtaining experimental values for collision velocity and collision angle prior to the barrier impact. Based on this, the relationship between collision angle, collision velocity, and highway alignment was analyzed. For the design of barriers on highway curves, Dai[3] proposed a novel flexible buffering barrier structure and employed numerical simulation calculations to analyze the vehicle collision process with the barrier, showing that the new buffering barrier structure can meet the protection requirements for road sections. Unlike permanent barriers, isolation barriers in maintenance work zones possess temporary characteristics. Li[4] studied the application scenarios of isolation barriers and, in combination with the MASH evaluation criteria, proposed protection levels and evaluation indicators for the

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design of isolation barriers. For vehicle collisions with barriers under different speed conditions, Liang[5] and Shi[6] conducted numerical simulation analyses, establishing vehicle collision barrier models and calculating injury to occupants and deformation indicators of the barriers. Different angles of a vehicle collision with barriers may influence the vehicle's travel posture and accident consequences. Zou[7], Xu[8], and Zhang[9] respectively analyzed the impact of vehicles at different angles on bridge piers, barriers, and crash cushions, obtaining dynamic indicators during the vehicle collision process and providing references for the structural design of relevant protective facilities. Furthermore, finite element analysis was used to simulate the collision process of cars with concrete bridges and barriers, and the reliability of the numerical simulation calculation method was further verified through analysis of the calculation results[10-12].

Existing studies have analyzed the structural collision process of vehicles under normal speed conditions, investigating the impact of factors such as collision velocity and collision angle on deformation and protective effects. The research findings provide certain references and guidance for the design and improvement of protective facility structures. However, further consideration is needed for the problem of vehicle collisions with barriers at super high-speeds. It is necessary to conduct further research on the collision between vehicles and barriers when the vehicles exceed the current normal speed conditions（120km/h）.

In this study, a numerical simulation analysis method was employed to model the dynamic collision process of vehicles colliding with roadside barriers at super high-speeds. The modeling process considered the influence of vehicle collision angles and simulated vehicle collisions with barrier structures at different angles. Relevant indicators of the vehicle's collision with the barrier at super high-speeds were obtained, providing a reference for subsequent barrier structure design.

2. CRASH TEST PROTOCOL

This study is conducted based on ongoing construction of a high-speed highway in China. The current design standards for certain sections of this highway are based on a design speed of 160 km/h for cars, while the speeds of other large and medium-sized vehicles are consistent with those of typical highways. Referring to the results of the "Investigation of Barrier Collision Accidents Involving Overturning and Running Off the Road" report by the Ministry of Construction and the Police Agency of Japan, the speed at which vehicles run off the road is determined as 80% of their traveling speed. Therefore, a car is chosen as the collision vehicle, and the collision speed is set at 130 km/h. Considering the impact of the vehicle's collision angle on occupant injury, vehicle travel posture, and barrier deformation, collision angles of 10°, 15°, 20°, 25°, and 30° are selected for analysis in the research process. The numerical simulation test scheme is presented in Table 1.

Table 1. Numerical simulation test scheme.

Barrier Type	Vehicle Type	Vehicle Mass	Collision Speed	Collision Angle
Metal Beam and Column Bridge Barrier	Small Passenger Car	1.5 t	130 km/h	10°
				15°
				20°
				25°
				30°

3. ESTABLISHMENT OF NUMERICAL MODELS

3.1. Vehicle model

The vehicle model is established based on a reference to a 1.5-ton car. The vehicle structure is constructed using shell elements and beam elements, and connections are made at the nodes. The established vehicle model is shown in Figure 1.

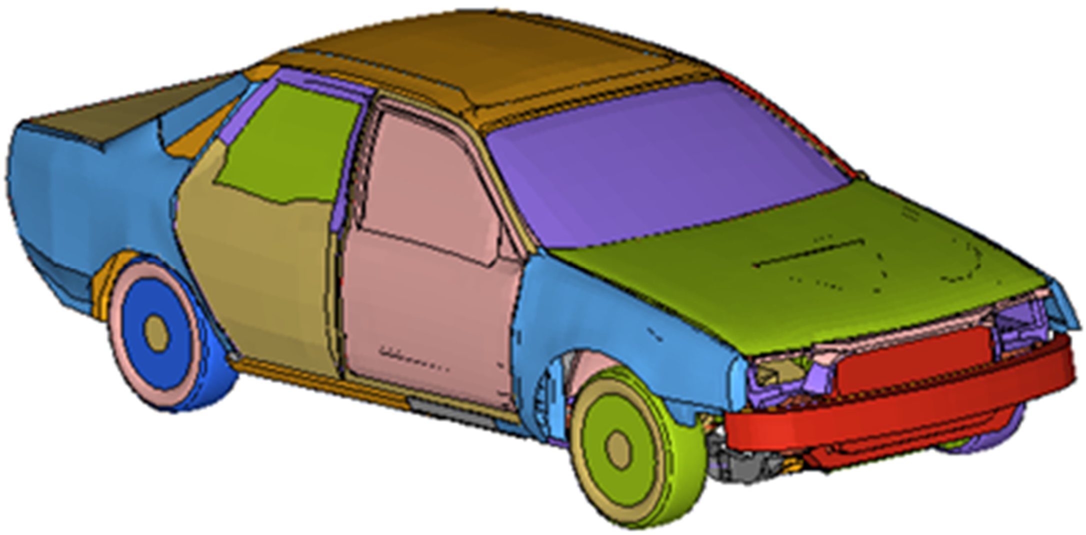


Figure 1. Vehicle model.

3.2. Guardrail Model

The guardrail model is established based on the design specifications of the actual road section, which features a metal beam and column bridge barrier. The guardrail has a height of 1.36m, a spacing of 1.5m between upright columns, a cross-sectional dimension of 140×140×6mm for the horizontal beam, and a thickness of 12mm for the column plates. The material used for the guardrail structure is Q345 steel. The established guardrail model is shown in Figure 2.

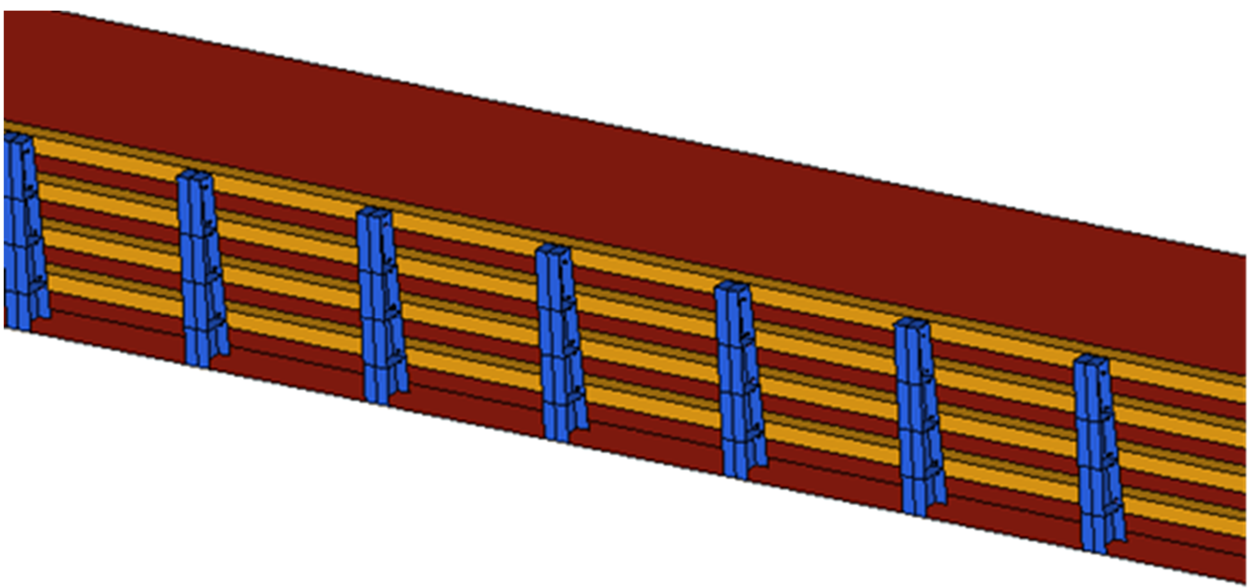
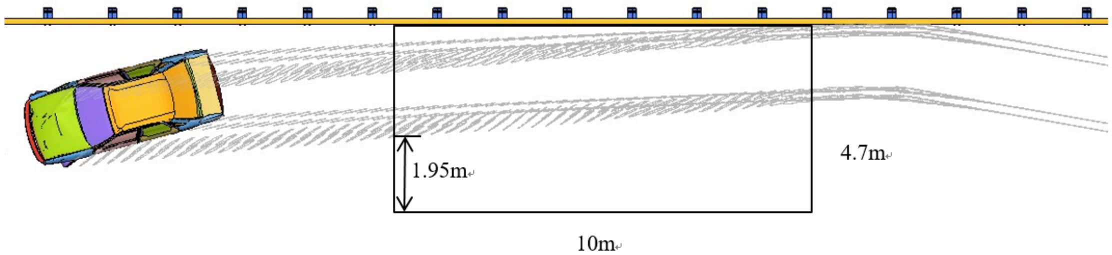


Figure 2. Guardrail model.

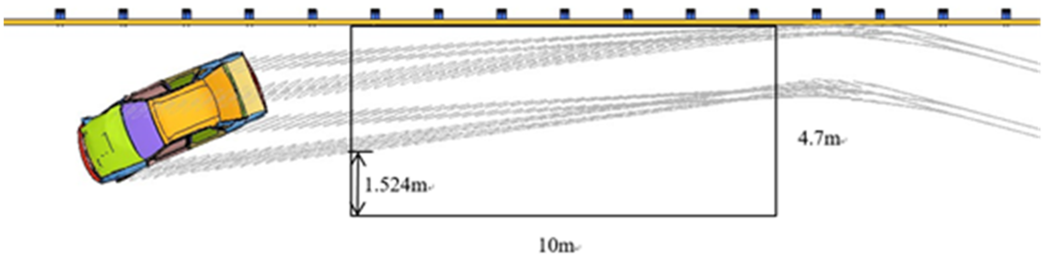
4. ANALYSIS OF COMPUTATIONAL RESULTS

4.1. Vehicle trajectory analysis

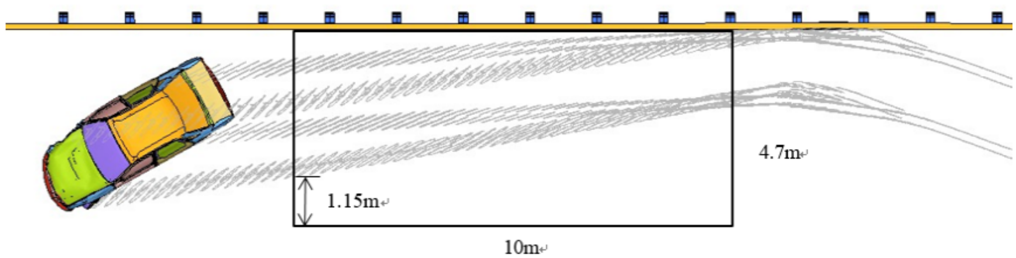
The driving trajectories of the vehicle during the collision with the guardrail are shown in Figure 3.



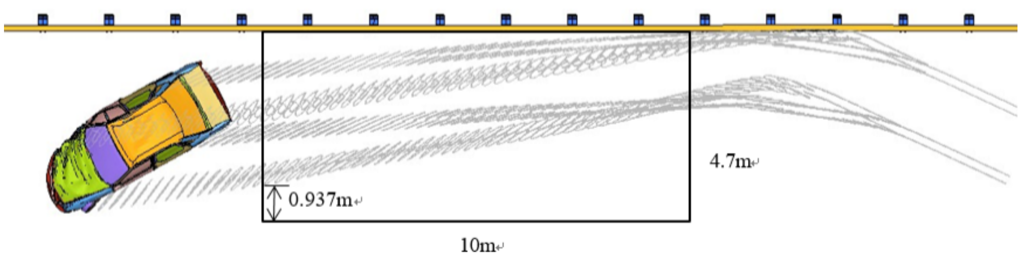
(a) 10°



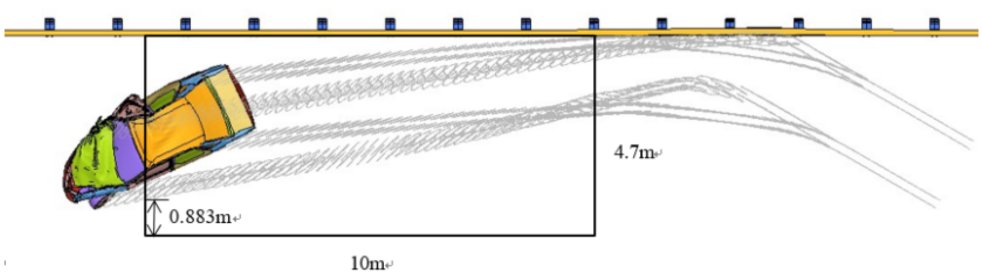
(b) 15°



(c) 20°



(d) 25°



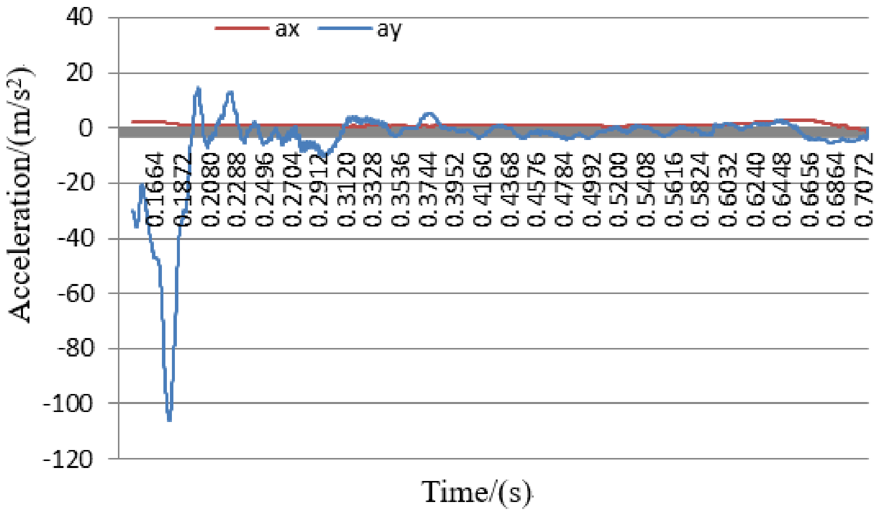
(e) 30°

Figure 3. Vehicle driving trajectory.

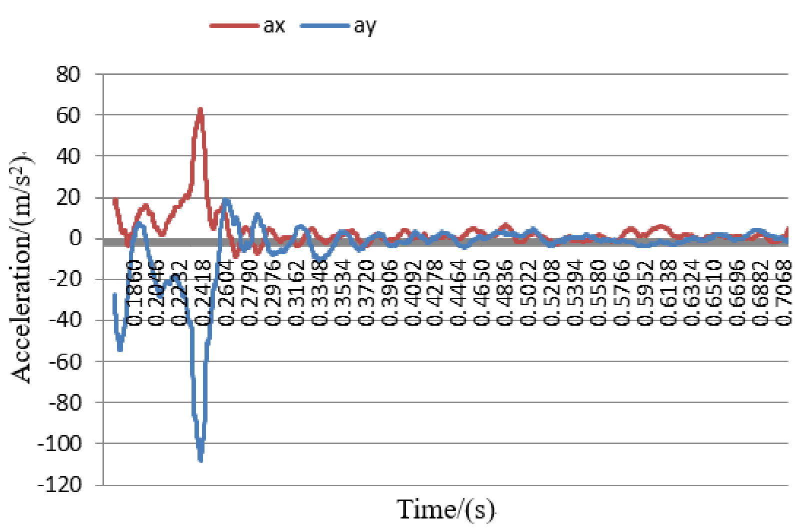
From the figures, it can be observed that during the collision of the high-speed vehicle with the guardrail at different angles, the vehicle has not experiences situations of rollover, penetration, and vaulting over the guardrail. The vehicle trajectories remain within the guiding exit box, indicating that the guardrail's guiding and buffering functions meet the requirements. By comparing the distance between the vehicle trajectory and the long side of the guiding exit box away from the guardrail, it can be observed that as the collision angle between the vehicle and the guardrail increases, the vehicle trajectory becomes closer to the long side of the guiding exit box away from the guardrail. This implies that in subsequent driving processes, there is a higher possibility of the vehicle entering adjacent lanes and adversely affecting the normal flow of traffic. Therefore, as the collision angle increases, the guiding function of the guardrail for the vehicle decreases.

4.2. Analysis of guardrail's buffering function

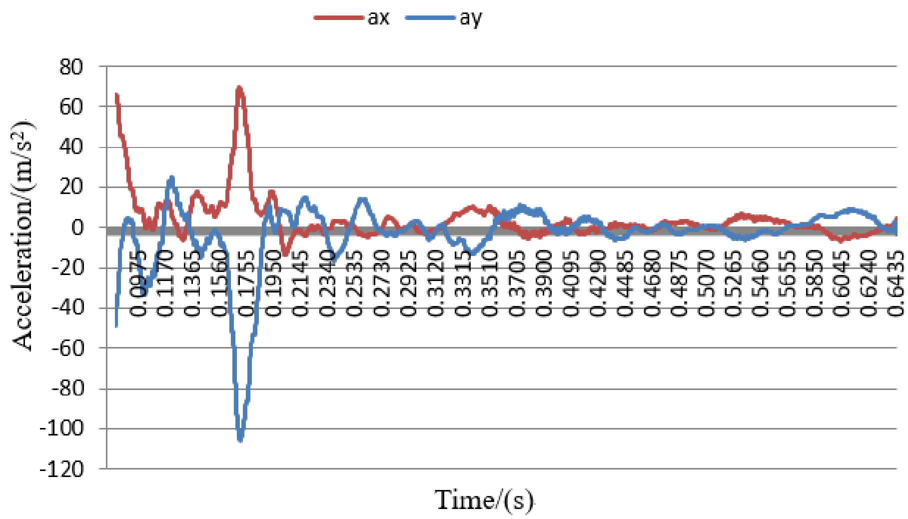
The center of gravity acceleration curve of the vehicle during the collision with the guardrail is shown in Figure 4, and the passenger collision velocity and acceleration is shown in Table 2.



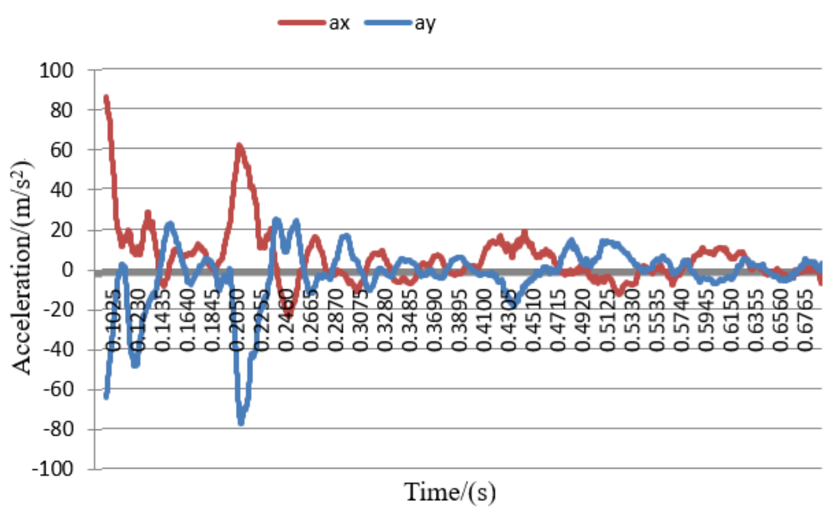
(a) 10°



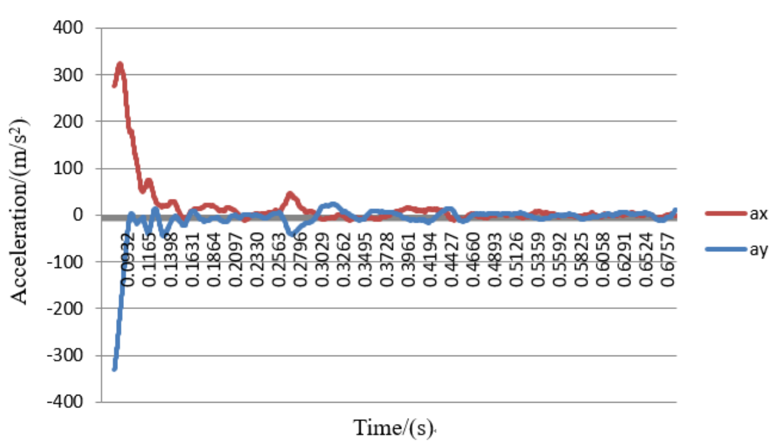
(b) 15°



(c) 20°



(d) 25°



(e) 30°

Figure 4. Gravity acceleration curve of the vehicle center.

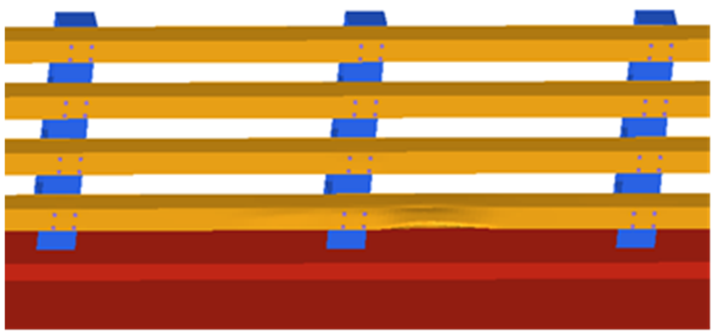
Table 2. Passenger collision velocity and acceleration.

Collision Angle (°)	Collision Velocity OIVx (m/s)	Collision Velocity OIVy (m/s)	Collision Acceleration OIAx (m/s2)	Collision Acceleration OIAy (m/s2)
10	2.22	5.62	3.12	106.14
15	5.40	8.17	62.84	108.13
20	7.61	10.82	69.86	105.75
25	9.99	11.45	85.89	77.50
30	12.25	12.55	324.29	329.36

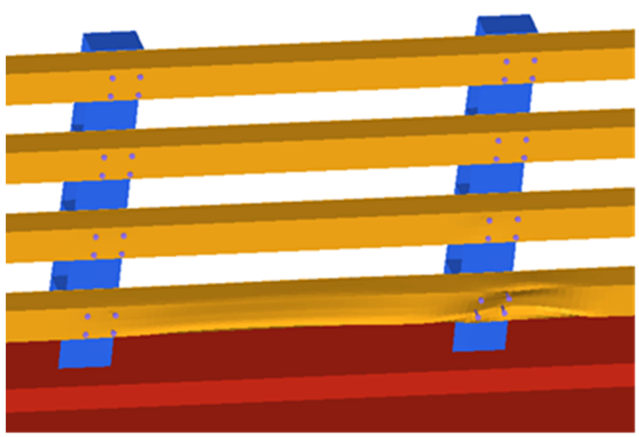
As the collision angle between the vehicle and the guardrail increased, the collision velocities in the x and y directions of the occupants exhibited an increasing trend. The x-directional collision acceleration of the occupants also showed an increasing trend, while the trend of y-directional collision acceleration was less evident. The data indicates that as the collision angle between the vehicle and the guardrail increases, the buffering effect of the guardrail on the vehicle decreases, leading to an increased risk of passenger injury. When the collision angle between the vehicle and the guardrail reaches 30 degrees, both the collision velocity and acceleration of the occupants exceed the threshold values specified in the "Highway Guardrail Safety Performance Evaluation Standard" (JTG B05-01-2013)(OIA not exceeding $200m/s^2$)(OIV not exceeding 12m/s), indicating that the buffering effect of the guardrail on the vehicle does not meet the requirements.

4.3. Analysis of guardrail deformation

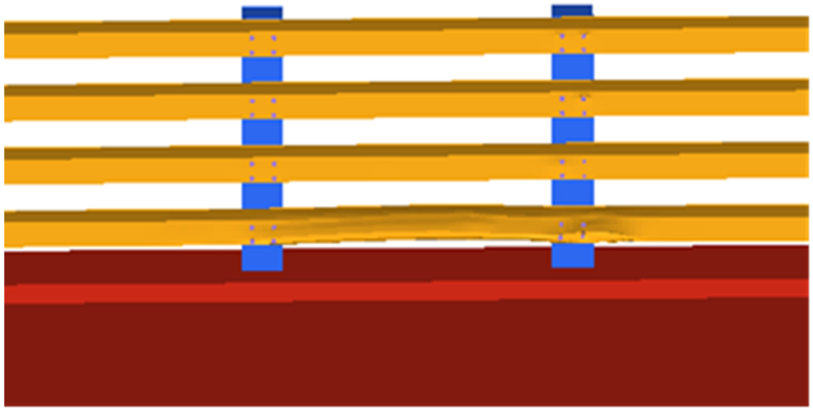
The deformation of the guardrail after the collision is presented in Figure 5.



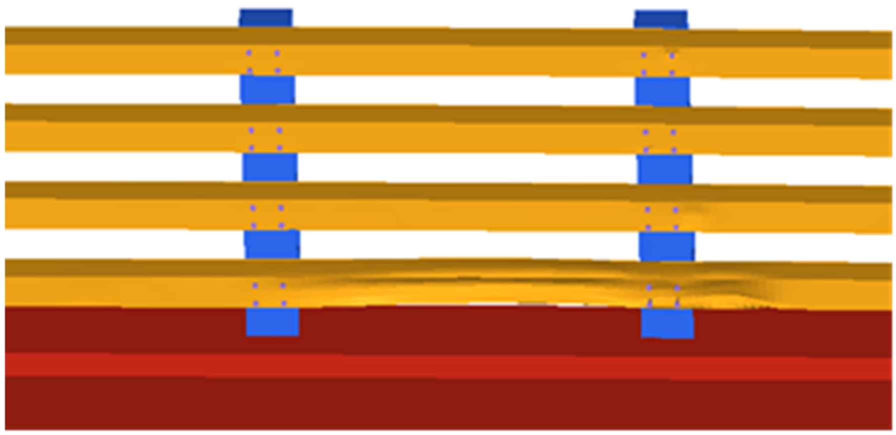
(a) 10°



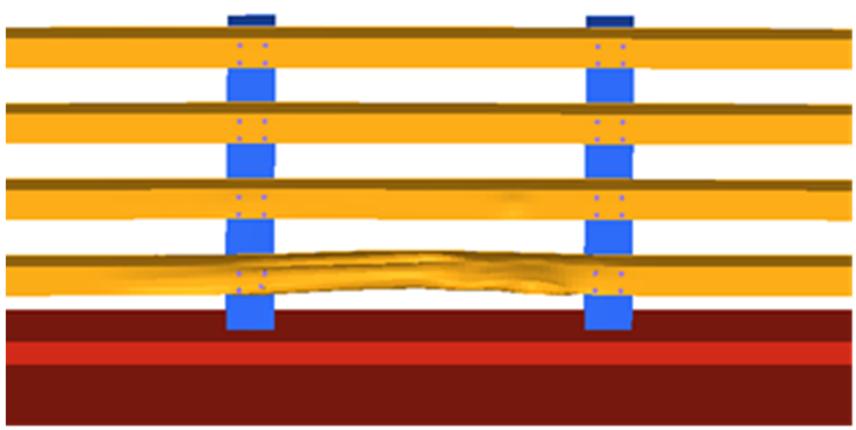
(b) 15°



(c) 20°



(d) 25°



(e) 30°

Figure 5. Deformation of guardrails after collision.

From the figure, it can be observed that as the collision angle (θ) between the vehicle and the guardrail increases, the deformation of the guardrail structure after vehicle collision becomes more severe. This is mainly attributed to the increased collision energy E (formula 1) exerted by the vehicle on the guardrail as the collision angle (θ) increases, resulting in a greater collision energy acting on the guardrail structure. Under the influence of higher collision energy, the deformation of the guardrail structure increases, indicating increased severity of vehicle collision with the guardrail.

$$E = \frac{1}{2} m (v \sin\theta)^2 \tag{1}$$

5. CONCLUSION

This study investigated the collision between high-speed car and guardrails. The relevant indicators during the collision process of bridge metal beam-column guardrails under different collision angles were analyzed. The main conclusions are as follows:

(1) During the collision between high-speed cars and guardrails at different angles, the vehicles have not exhibited tendencies of overturning, penetrating, and riding over the guardrails. The trajectories of the vehicles remained within the guiding and exiting frame, indicating that the guiding and buffering functions of the guardrail structure met the requirements. As the collision angle between the vehicle and the guardrail increased, the vehicle trajectories gradually approached the long side of the guiding and exiting frame away from the side of the guardrail, resulting in a decrease in the guiding function of the guardrail.

(2) With an increasing collision angle between the vehicle and the guardrail, the buffering effect of the guardrail on the vehicle decreased, leading to an increased risk of passenger injury. When the collision angle between the vehicle and the guardrail reached 30 degrees, both the collision velocity and acceleration of the passengers exceeded the limits specified in the "Highway Guardrail Safety Performance Evaluation Standard" (JTG B05-01-2013) (OIA not exceeding 200m/s^2) (OIV not exceeding 12m/s), indicating that the buffering effect of the guardrail on the vehicle did not meet the requirements.

(3) As the collision angle between the vehicle and the guardrail increased, the collision energy exerted by the vehicle on the guardrail increased, resulting in an increased collision energy acting on the guardrail structure. Under the influence of the larger collision energy, the deformation of the guardrail structure increased, indicating increased severity of the vehicle collision with the guardrail.

(4) This study focused on the simulation analysis of high-speed car collisions with bridge metal beam-column guardrails. Subsequent research will investigate the collisions of high-speed vehicles with waveform beam guardrails and concrete guardrails. In summary, this research provides insights into the collision between high-speed car and guardrails. The findings emphasize the impact of collision angles on vehicle trajectories, passenger safety, and guardrail performance. The results highlight the need for further research on guardrails, including different types of guardrails, to enhance their safety and effectiveness in preventing accidents.

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