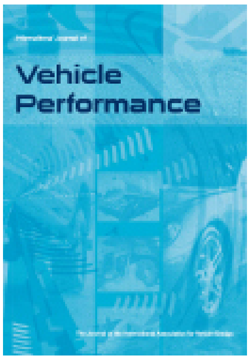

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Research on impact resistance of steel wheel considering vehicle effect

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Abstract: Although there is no public standard for 90° impact test of steel wheel, some wheel manufactures have introduced the impact test to ensure the safety performance of steel wheel. It is often referred to the standard methods used for light alloy wheels. However, whether light alloy wheel 90° impact test methods are applicable to steel wheels have not been studied. In this paper, the vehicle model and road model were established in ADAMS/Car to simulate the vehicle passing through bumps and potholes. The maximum impact force on the wheel was obtained by changing vehicle speed and obstacle size. The simulation result of the wheel under the maximum impact force was compared with those of the 90° bench impact tests. The results show that test method I of 90° impact standard for light alloy wheels is applicable to steel wheels and test method II is too stringent for steel wheels.

Keywords: 90° impact; steel wheel; vehicle effect; test standard; ADAMS/Car; impact resistance.

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1 Introduction

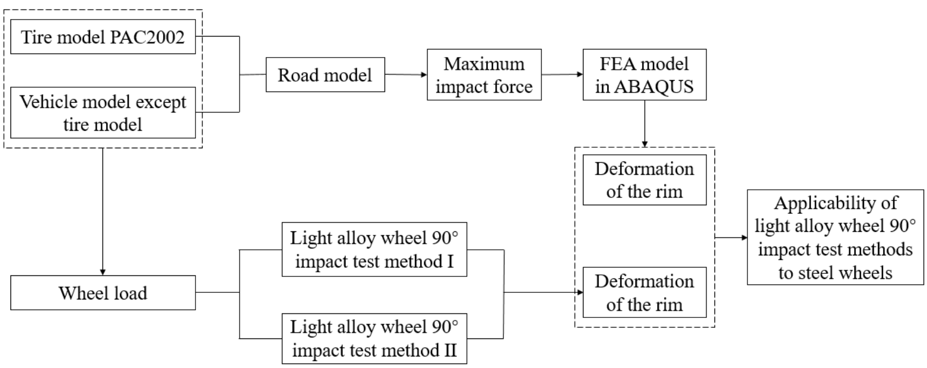
The wheel is one of the important parts in the vehicle and has an important effect on the safety performance of the vehicle. It must pass the dynamic rotating bending test and the dynamic radial fatigue test. Light alloy wheels also must pass the impact tests, including 13° impact test and 90° impact test. The 90° impact test is used to evaluate the strength and safety performance of the wheel when it is impacted perpendicular to the axis, simulating the load environment of the wheel when the vehicle runs through bumps and potholes or runs in other harsh road conditions. The wheel may fail in an instant under these conditions (Yin, 2013). Under normal circumstances, steel wheels have good impact resistance. Therefore, there is no mandatory impact test requirement for steel wheels. However, the damage of steel wheels caused by impact occasionally occurs in the actual use (Gao et al., 2019). To ensure the wheel's safety performance, some wheel manufactures also introduce the 90° impact test for the steel wheel. However, whether light alloy wheel 90° impact test methods can be applied to steel wheels should be studied.

The bench test and road test are costly and time-consuming, so virtual simulation methods are often adopted to study the wheel impact resistance. Yin et al. (2013) studied the impact characteristics of the steel wheel considering strain rate effect; Gao et al. (2019) established and verified the simulation model for 90° impact test of steel wheels. Jiang (2017) only established the wheel-tyre assembly model to study the impact force on the wheel when passing through obstacles. Ren (2009) analysed the influence of the size of speed bump on the ride comfort and safety of the vehicle based on ADAMS/Car; Hu (2012) built the 3D random road and 3D pulse road in ADAMS/Car for ride comfort analysis; Zhang et al. (2017) established the vehicle model in ADAMS/Car and simulated the steady turning test. Most scholars mainly use multi-body dynamics software to study the ride comfort and handling stability when the vehicle runs in harsh road conditions and rarely pay attention to the force on the wheel. The existing studies (Chang and Yang, 2009; Cerit, 2010; Wang et al., 2019; Zhang, 2018; Neves et al., 2010; Xiong et al., 2019) mainly focus on the impact test of aluminium alloy wheels. There were few about 90° impact test simulations of steel wheels. And in the existing research, light alloy wheel

90° impact test methods were directly used to study the impact resistance of steel wheels. Whether the methods can be applied to steel wheels have not been studied. Besides, most scholars study the impact resistance by bench tests. The actual impact process can be simulated in ADAMS/Car, while only the wheel-tyre assembly of the vehicle are included in the bench test. There is a lack of research on studying wheel impact resistance considering the actual impact process by multi-body dynamic software. It is necessary to study the impact resistance of steel wheels considering vehicle effect and verify the applicability of light alloy wheel 90° impact test methods to steel wheels.

In this paper, the vehicle model and road model are established in ADAMS/Car and the impact force on the wheel is extracted when the vehicle passes through bumps and potholes. The maximum impact force is obtained when the vehicle passes the obstacles by changing the vehicle speed and obstacle size. Then deformation of the rim is simulated under the maximum impact force in ABAQUS. The simulation result is compared with those of 90° bench impact test methods to analyse the applicability of light alloy wheel 90° impact test methods to steel wheels. The flowchart of this study is shown in Figure 1.

Figure 1 The flowchart of this study



2 Establishment of simulation model of vehicle passing bumps and potholes in ADAMS/Car

Tyre is one of the most important parts of the vehicle and has a great influence on the vehicle performance. The PAC2002 tyre model in the ADAMS/Car database using magic formula is adopted in this paper. This tyre model has high accuracy and can meet the simulation requirements. The tyre size is 195/65R15 and the tyre model is shown in Figure 2.

Because this paper focuses on the force between the tyre and the ground, the MDI demonstration vehicle model in the ADAMS/Car database is adopted to facilitate modelling. Then replace the original tyre with the tyre described above. The new vehicle model is shown in Figure 3. The wheelbase is 2560 mm and distance from vehicle centroid to the front axle is 1484.73 mm. The vehicle mass is 1507.68 kg.

Figure 2 PAC2002 tyre model in the ADAMS/Car database

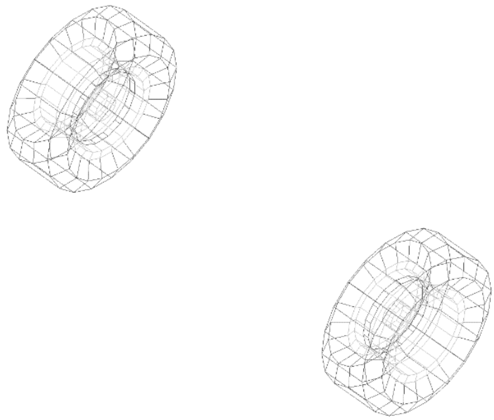
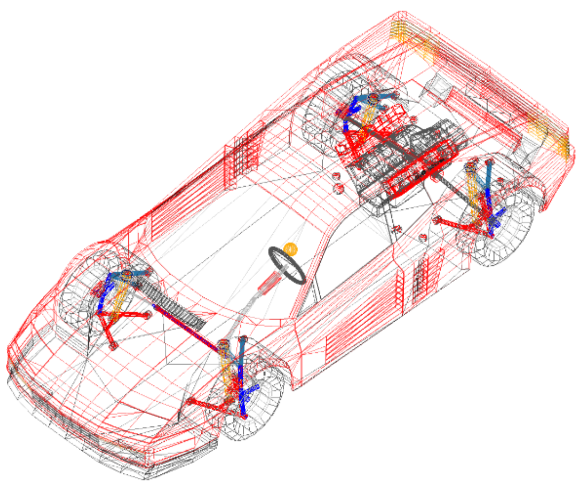


Figure 3 Vehicle model in the ADAMS/Car database with tyres replaced by pac2002 tyre model (see online version for colours)

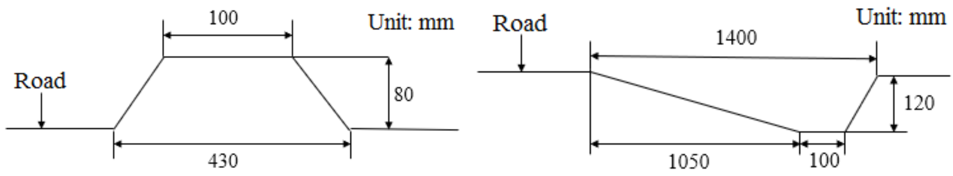


There are 2D and 3D road models in ADAMS/Car and both can define the shape of the road. In order to observe the simulation results more intuitively, this paper uses 3D road for simulation. 3D road can be divided into equivalent volume road and spline road. 3D spline road model defines the road shape by the centreline of the road, mainly including three-dimensional coordinates of the calibration points on the centreline, the width of the road and the friction coefficient. Obstacles can be established on special roads, including the plank, pothole, polyline, crown and so on.

A company's road test requires the vehicle to drive over the road with obstacles shown in Figure 4.

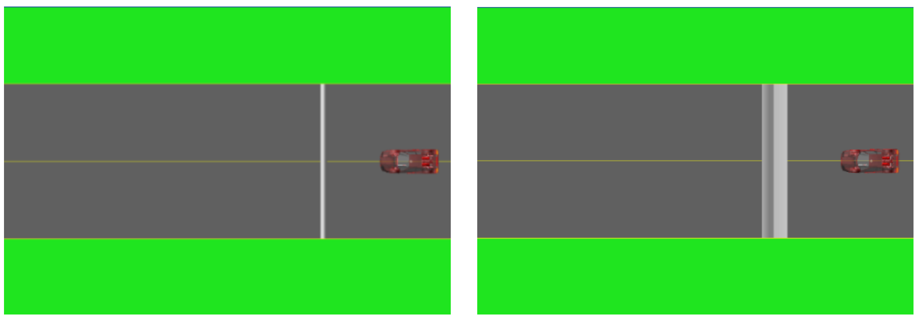
According to the test requirements, the bump and pothole consistent with Figure 4 are established by defining the positions of key points, as shown in Figure 5.

Figure 4 Obstacle shape adopted by the company: (a) bump and (b) pothole



(a) (b)

Figure 5 Road model and vehicle model: (a) road with bump and (b) road with pothole (see online version for colours)



(a) (b)

3 Simulation results under the maximum impact force obtained by full-vehicle analysis in ADAMS/Car

3.1 Simulation of vehicle passing through the bump and pothole at different speeds

The vehicle passes through the road with bump and pothole at different speeds. Select vehicle speeds from 20 km/h to 100 km/h for simulation. The increment is 10 km/h and simulation type is straight-line maintain. Simulation time is 3 s and the number of steps is 300. In the post-processing module, the variation curve of vertical force between the wheel and the ground can be obtained. The change of impact force on the four wheels is similar. Select the right front wheel for analysis and the change of tyre force when the vehicle passes through the bump and pothole at 60 km/h is shown in Figure 6.

The static load of right front wheel is 3086 N. When the vehicle passes through the bump or pothole, the wheel suffers a frontal impact and the force on the tyre increases dramatically. The coefficient K is defined as the maximum impact force divided by the static load of the right front wheel. The change of K when the vehicle passes through the bump and pothole at different speeds is shown in Figure 7.

$$K = \frac{F_{\max}}{F_{static}} \tag{1}$$

where $F_{\max}$ is the maximum impact force; F_{static} is the static load of the wheel.

Figure 6 The change of tyre force when the vehicle passes through the bump and pothole at 60 km/h (see online version for colours)

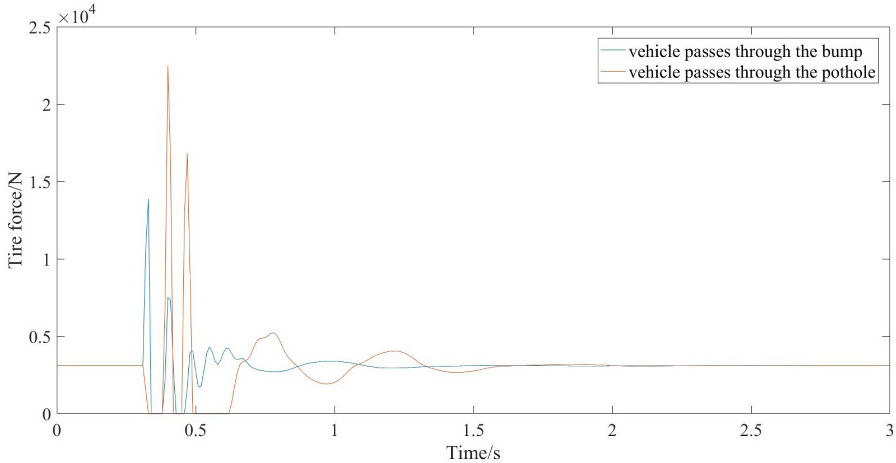
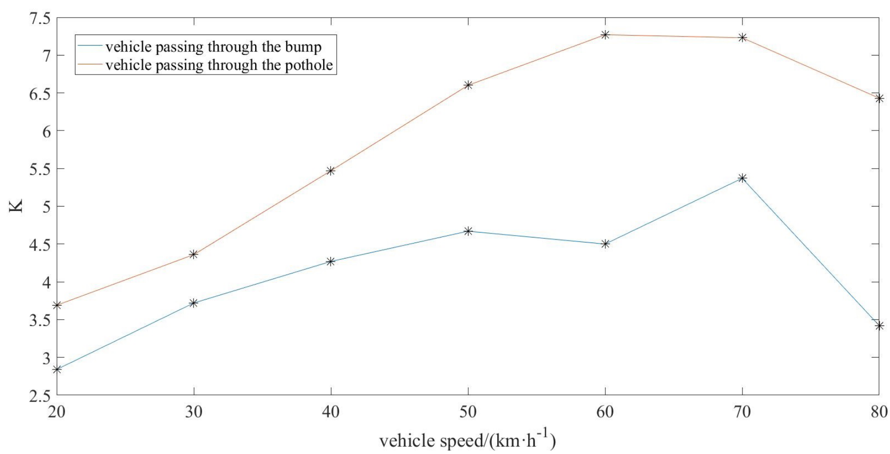


Figure 7 The change of *K* when the vehicle passes through the bump and pothole at different speeds (see online version for colours)



It can be seen from Figure 7 that within a certain speed range, the maximum impact force increases with the increase of vehicle speed. Under this road test method, when the vehicle speed is the same, the maximum impact force when the vehicle passes through the pothole is greater than when passing the bump. The test of vehicle passing through the pothole is more stringent. The impact force is maximum when the vehicle speed is 60 km/h,

3.2 Simulation of the vehicle passing through obstacles with different sizes at 60 km/h

In order to study the influence of obstacle size on the impact force, the depth of the pothole and the height of the bump in the road model described in Section 2 are changed and the other dimensions remain unchanged.

Road models with bump heights from 50 mm to 110 mm and pothole depths from 90 mm to 150 mm are established respectively and the increment is 10 mm. The vehicle passes through the bump and pothole at 60 km/h. The change of *K* when the vehicle passes through obstacles with different sizes is shown in Figures 8 and 9.

Figure 8 The change of *K* when the vehicle passes through bumps with different heights at 60 km/h

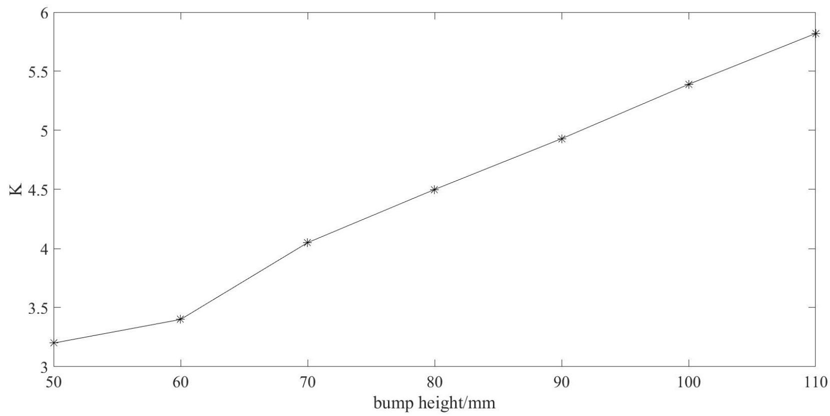
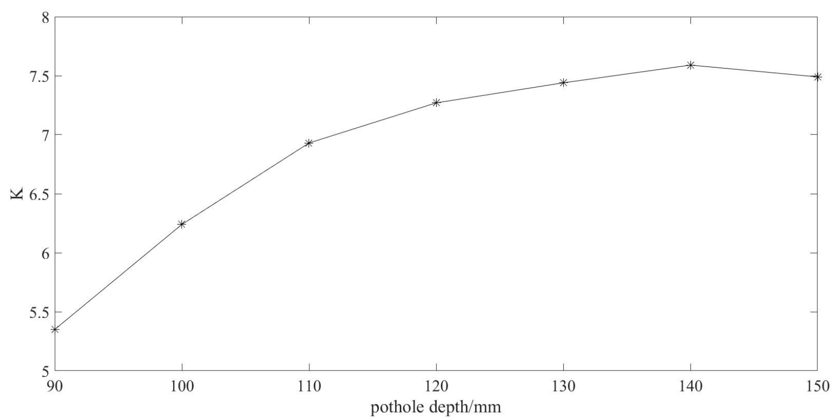


Figure 9 The change of *K* when the vehicle passes through potholes with different depths at 60 km/h



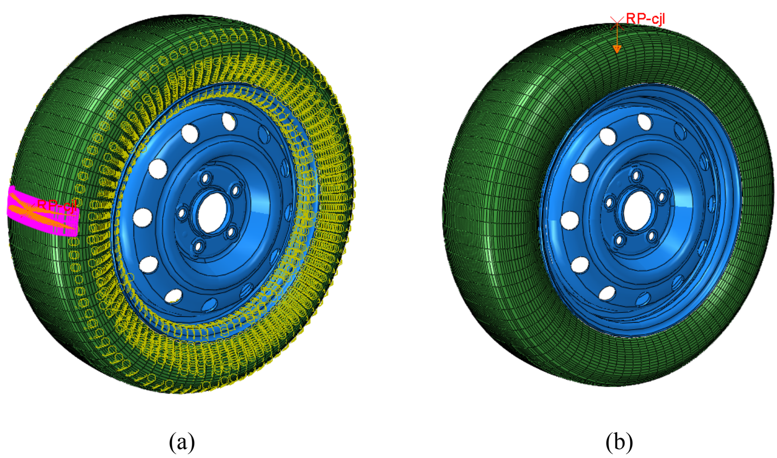
It can be seen from Figures 8 and 9 that within a certain range, the maximum impact force increases with the increase of obstacle size. The maximum impact force is 23426.12 N when the vehicle passes through the pothole at 60 km/h.

3.3 Simulation of rim deformation under the maximum impact force

It can be concluded from Sections 3.1 and 3.2 that both the vehicle speed and obstacle size will affect the impact force on the wheel. Among the above simulation results, the maximum impact force occurs when the vehicle passes through the pothole with a depth of 140 mm. The value is 23426.12 N, which is about 7.59 times the static load of the wheel. One enterprise used six-component force sensors to measure the maximum impact force when passing the pothole. The value is 6–8 times the static load of the wheel. The simulation result is within this range, verifying the effectiveness of the simulation model.

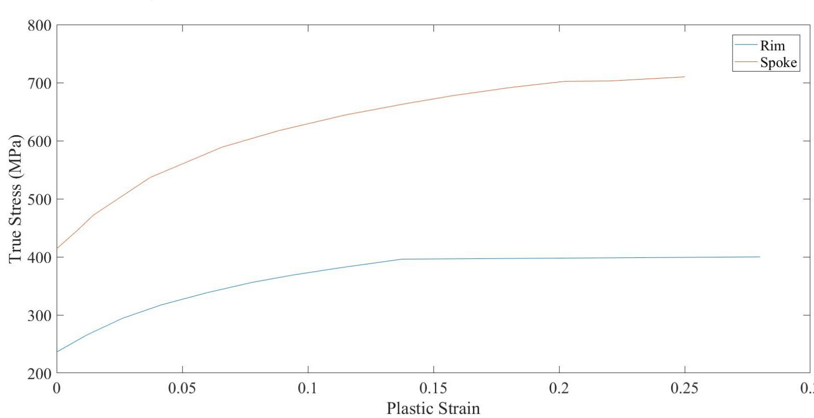
The wheel-tyre assembly model is built in ABAQUS to simulate the deformation of the rim under the maximum impact force. To match the vehicle model in ADAMS/Car, the selected rim specification is 15 × 5.5 J. Select elements of the tyre at the impact position, couple them to the central reference point (RP-cjl in Figure 10), and then apply the force to this reference point. Fix mounting surface of the wheel, as shown in Figure 8. The rim is tied to the tyre and spoke. Tyre pressure is 0.2 MPa and it is applied to the outer surfaces of the rim and inner surfaces of the tyre.

Figure 10 Wheel-tyre assembly simulation model: (a) coupling elements to reference point and (b) applying impact force to reference point (see online version for colours)



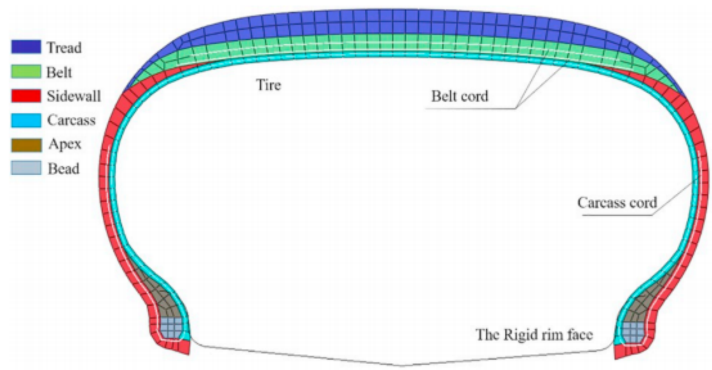
For the rim and spoke, the material density is 7.8×10^3 kg/m^3; the elastic modules is 195 GPa; the Poison's ratio is 0.3; the tensile strengths of the steels are 380 MPa and 600 MPa, respectively. The hardening characteristics is included and the hardening curves of the rim and spoke materials are shown in Figure 11.

Figure 11 Hardening characteristics of steel materials (rim and spoke) (see online version for colours)



The cord-rubber composite tyre model including the tread, belt, sidewall, carcass, apex and bead is established, as shown in Figure 12. The property of the tyre rubber is expressed by using the Yeoh model (Yeoh, 1993) which has high fitting precision in the case of large deformation to describe constitutive relations. There are three parameters C_{10}, C_{20} and C_{30} describing the shear properties of the material in the model. The values are shown in Table 1. The cord material parameters are shown in Table 2. The 3D tyre model is obtained by rotating 2D model and the tread pattern is ignored since the negligible influence on the simulation results.

Figure 12 Two-dimensional tyre finite element model (see online version for colours)



Source: Wan (2017)

Table 1 Rubber material parameters in tyres

Part name	*Density*(t/mm^3)	C_{10}	C_{20}	C_{30}
Tread	1.173e-9	0.585	–0.195	0.077
Sidewall	1.11e-9	0.466	–0.153	0.045
Belt	1.18e-9	0.945	–0.281	0.118
Carcass	1.15e-9	0.797	–0.235	0.089
Apex	1.175e-9	1.606	–0.566	0.280

Table 2 Cord material parameters

Material name	*Young's modules* (MPa)	*Poisson's ratio*	*Material density* (t/mm^3)	*Sectional area* (mm^2)	*Cord spacing* (mm)	*Angle with the tyre meridian plane* (°)
Carcass	9597	0.4	1.14e-9	0.241	1.00	0
Belt 1#	210205	0.3	7.8e-9	0.141	1.176	63
Belt 2#	210205	0.3	7.8e-9	0.141	1.176	117
Bead	210000	0.3	7.8e-9	0.723	1.35	–

The mesh type of the rim and spoke is C3D4 and the tyre rubber matrix is discrete by C3D8R and C3D6 elements. Set the simulation time to 0.15 s and the impact force to reach the maximum value of 23426.12 N at 0.075 s (the maximum impact force on the right front wheel when passing through the pothole with a depth of 140 mm at 60 km/h). Using ABAQUS for simulation, the maximum deformation of the rim is 1.40 mm and the final deformation of the rim is 0.061 mm.

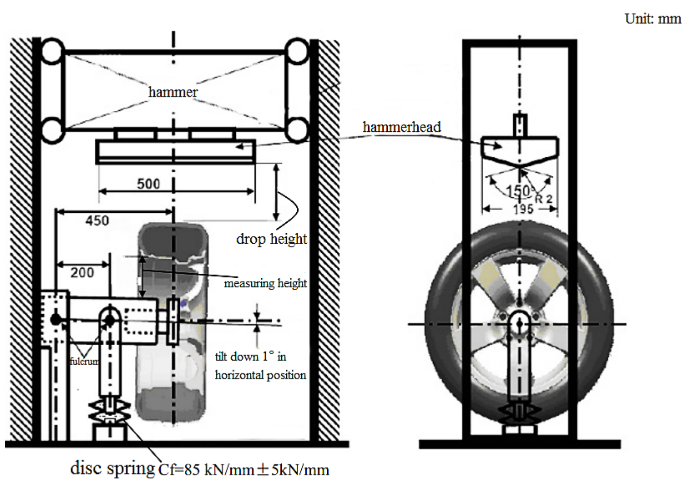
4 Simulation of wheel 90° bench impact test

Two test methods are specified in the wheel 90° impact test standard (QC/T 991-2015) to evaluate the strength and safety performance of the wheel when it is impacted perpendicular to the axis.

4.1 Simulation of rim deformation based on test method I

The equipment diagram of test method I is shown in Figure 13, which is mainly composed of a hammer, wheel-tyre assembly and a mounting bracket.

Figure 13 Equipment diagram of test method I



The basic mass of the hammer is 150 kg, the maximum mass is 315 kg, and the minimum adjustable mass is 5 kg; disc spring preload is 0.2 mm; the recommended tyre inflation pressure is 200 kPa, which can float up and down 10 kPa.

The impact energy is set as

$$E = K \times F_r \tag{2}$$

where E(J) is the impact energy; K(J/kg) is the coefficient, with two values of 1.15 and 4.3. 1.15 is used in this paper; F_r(kg) is the maximum static load of the wheel specified by the manufacturer, which is the static load of the wheel in this paper.

Test requirements: there should be no cracks on the wheel after impact; deformation of the inner rim should not exceed 2.5 mm.

Establish the simulation model of test method I in ABAQUS, as shown in Figure 14. Set the hammer as a rigid body and the hammer is imposed an initial velocity. The variation curve of rim deformation is shown in Figure 15. The maximum impact force is

20,782 N. The maximum deformation of the rim is 1.26 mm and the final deformation of the rim is 0.004 mm.

Figure 14 Simulation model of test method I (see online version for colours)

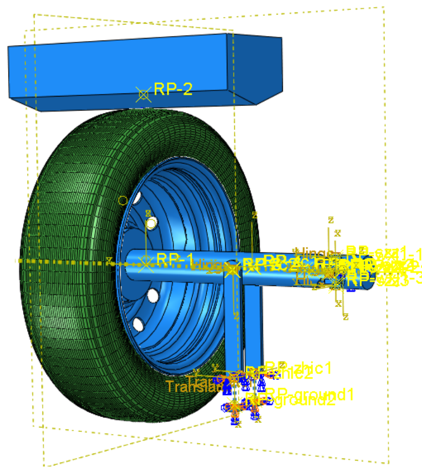
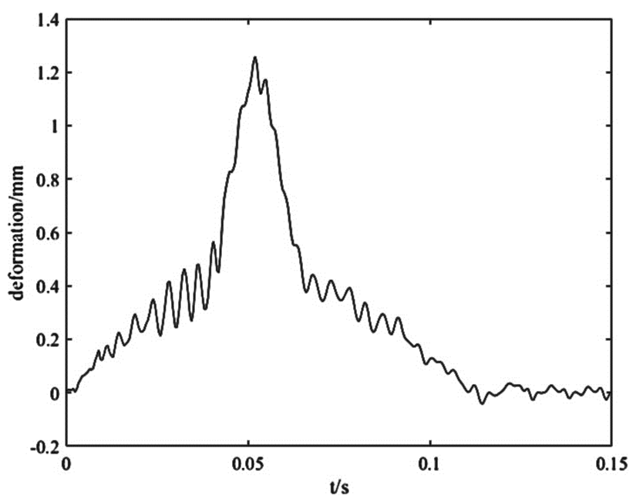


Figure 15 Variation curve of rim deformation (test method I)

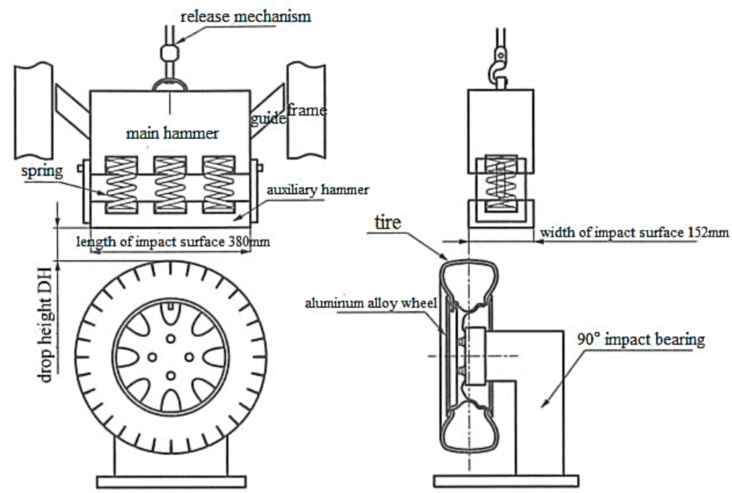


4.2 Simulation of rim deformation based on test method II

The equipment diagram of test method II is shown in Figure 16, which is mainly composed of hammers, wheel-tyre assembly and a mounting bracket.

Main hammer mass (including spring mass): 910 ± 18 kg; auxiliary hammer mass: 100 ± 4.5 kg; there are at least two springs, the total stiffness is 0.98~1.3kN/ mm and the spring preload is 6 mm; the recommended tyre inflation pressure is 200 kPa, which can float up and down 10 kPa.

Figure 16 Equipment schematic diagram of test method II



The drop height of the hammer is set as

$$H = K \times F_r \tag{3}$$

where H(mm) is the drop height; K(mm/kg) is the coefficient; F_r(kg) is the maximum static load of the wheel specified by the manufacturer, which is the static load of the wheel in this paper.

Test requirements: there should be no cracks on the wheel after impact; deformation of the inner rim should not exceed 2.5 mm.

Establish the simulation model of test method II in ABAQUS, as shown in Figure 17. Fix mounting surface of the wheel. Set hammers as rigid bodies and connect main hammer and auxiliary hammer by springs. The variation curve of rim deformation is shown in Figure 18. The maximum impact force is 38,979 N. The maximum deformation of the rim is 11.6 mm and the final deformation of the rim is 4.8 mm.

Figure 17 Simulation model of test method II (see online version for colours)

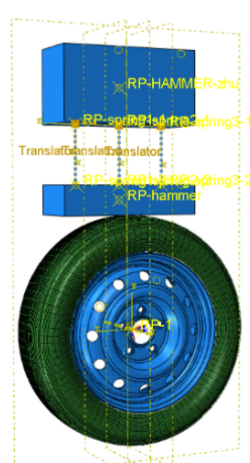
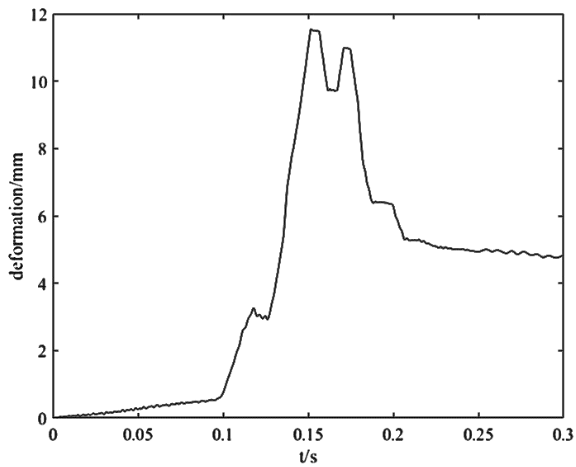


Figure 18 Variation curve of rim deformation (test method II)



5 Analysis of simulation results

In Section 3 of this paper, the vehicle effect is considered to obtain the maximum impact force when the vehicle passes through bumps and potholes. Then rim deformation is simulated in ABAQUS under this force. In Section 4 of this paper, the maximum impact load and rim deformation are obtained based on two 90° bench impact test methods. The results are shown in Table 3.

Table 3 Comparison of simulation results

Simulation model	*Maximum impact force/N*	*Maximum deformation of the rim/mm*	*Final deformation of the rim/mm*
90° impact standard (test method I)	20,782	1.26	0.004
90° impact standard (test method II)	38,979	11.6	4.8
Vehicle model in ADAMS/Car	23,426.12	1.40	0.061

It can be concluded from Table 3 that the maximum impact force of test method I is about 0.9 times of the vehicle simulation model. Maximum deformation of the rim is 1.26 mm, which is close to result of the vehicle simulation model. Final deformation of the rim is 0.004 mm. According to the test requirements, it is less than 2.5 mm, which can pass the 90° bench impact test. The maximum impact force of test method II is about 1.7 times of the vehicle simulation model. Load case of the wheel simulated by this method is worse than that of the model considering the vehicle effect. In this test method, the hammer only impacts half of the tyre, which leads to worse load environment of one side of the rim. The maximum deformation of the rim is 11.6 mm. Final deformation of the rim is 4.8 mm. According to the test requirements, it exceeds 2.5 mm, which cannot pass the 90° bench impact test. The above simulation results show that test method I of current 90° impact standard applied to light alloy wheels is applicable to steel wheels and test method II is too stringent for steel wheels.

6 Conclusions

In this paper, ADAMS/Car is used to simulate the vehicle passing through bumps and potholes. The maximum impact force is obtained when the vehicle passes the obstacles by changing vehicle speed and obstacle size. Deformation of the rim under the maximum impact force is compared with that obtained by two bench test methods. The conclusions are as follows:

1 The impact force is obtained when the vehicle passes through bumps and potholes considering vehicle effect. The ratio of the maximum impact force to the static load of the wheel is 7.59. The ratio measured by an enterprise using six-component force sensors is 6–8, verifying the effectiveness of the vehicle simulation model.

2 When the vehicle passes through bumps and potholes with the shape used by the enterprise in road test at the same speed, the maximum impact force when passing through potholes is larger than that when passing through bumps, indicating that the test of the vehicle passing through potholes is more stringent.

3 Test method I of current 90° impact standard applied to light alloy wheels is applicable to steel wheels and test method II is too stringent for steel wheels.

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