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Comparative Analysis of Static Loading Performance of Rigid and Flexible Road Wheel based on Finite Element Method

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ABSTRACT

To overcome the shortcomings of traditional rigid road wheel, such as poor damping effect and low load-bearing efficiency, a new type of flexible road wheel, having a unique suspension-bearing mode, was introduced. The three-dimensional nonlinear finite element model of rigid and flexible road wheel, considering the triple nonlinear characteristics of geometry, material and contact, is established for numerical investigation of static loading performance. The accuracy of the finite element model of the rigid and flexible road wheel is verified by static loading experiment. The static loading performance of the rigid and flexible road wheels is numerically analyzed. The influence of vertical load on maximum stress and deformation of the rigid and flexible wheels is also studied. The results show that the contact pressure uniformity of the flexible road wheel is better than that of the rigid road wheel under the static vertical load, but the maximum stress and deformation of the flexible road wheel are greater than that of the rigid road wheel. However, this problem can be solved by increasing the number of hinge sets and optimising the joints. The research results provide theoretical basis for replacing rigid road wheel with flexible road wheel, and also provide reference for structural optimisation of flexible road wheel.

Keywords: Rigid road wheel; Flexible road wheel; Finite element method; Static loading performance; Contact characteristic

1. INTRODUCTION

The high protection, manoeuvrability, passability, unmanned and lightweight are the future development trends for the ground mobile platform. The tracked vehicles occupy an extremely important position in the ground mobile platform and play an important role in the military field because of its good passability[1]. The track propulsion device of tracked vehicles is a major breakthrough after the invention of the wheel, which provides a continuous rolling track for the road wheel, and can be regarded as a movable road carried by the tracked vehicle[2]. The track propulsion device allows the vehicle to travel smoothly on off-road surfaces at a higher speed and overcome a variety of natural and artificial obstacles.

Tracked vehicles often pass through rugged fields, trenches, low walls and soft ground, which will result in strong vibrations. The harm caused by the vibration has a great impact on the environment and the health of the driver and passengers. So far, most tracked vehicles are equipped with road wheels with a rigid structure, and its vibration reduction effect is unsatisfactory. In addition, the weight of rigid road wheels is generally heavy, which greatly affects the lightweight level and limits the further performance improvement of tracked armoured vehicles.

In view of the shortcomings of the rigid road wheels, many scholars have done a lot of research on the structure and material of road wheels. Many new materials such as E-glass fiber/epoxy composites, carbon fiber reinforced epoxy composites, aluminum alloys, etc. are used in the manufacture of road wheels to reduce the weight of road wheels[3]. There are also some new type of flexible road wheels that contain different damping elements that have been invented to mitigate vehicle vibration[4-5]. Although these research have achieved some beneficial effects, they have not fundamentally broken through the solid structure and the common problems such as curling damage and low carrying efficiency still exist. To this end, a new type of flexible road wheel that uses several connecting parts (hinge sets) to connect the rim and hub, offering higher flexibility for the road wheel[6-7] is proposes. Compared to traditional rigid road wheel, the flexible road wheel has a higher bearing efficiency and good vibration damping performance.

As far as we know, the main research objects in the past are pneumatic tires and non-pneumatic wheels. There are few studies on the road wheels of tracked vehicles. Therefore, in this paper, the mechanical properties of rigid and flexible road wheels under static loading condition are studied using finite element method. The effects of vertical load on the maximum stress and deformation of the rigid and flexible road wheel are also analysed. The accuracy of the finite element (FE) model of flexible road wheel is verified by static loading experiment. The research results can provide theoretical foundation for the further application of the flexible road wheel to the tracked vehicle, and also provide reference for the structural design of the flexible road wheel.

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2. STRUCTURE AND BEARING MECHANISM OF FLEXIBLE ROAD WHEEL

2.1 Structural Description

The main structure of the flexible road wheel consists of three parts: the hinge set, elastic outer ring and hub. The overall structure is as shown in Fig. 1. The relationship between the various components is as follows. Twelve hinge sets are evenly distributed around the circumference to connect the elastic outer ring and hub, and thus the hub is in a suspended state[8]. Each hinge set is composed of three hinge bodies connected by a pin shaft, so that the hinge set has a certain flexibility. The elastic outer ring consists of five elastic rings, twelve combination cards and vulcanised rubber. The combination cards are circumferentially evenly distributed to fix five elastic rings wound by spring wire. At the same time, it is connected with the hinge sets by the middle lug to realise the transmission of force.

2.2 Bearing Mechanism

Figure 2 displays the load-bearing mechanism of the rigid road wheel and flexible road wheel. The load-bearing mode of the rigid road wheel is termed as "bottom bearing", because only the portion of the wheel contacted with the track is subjected to load. The load bearing mode of the flexible road wheel is called "suspension bearing", that is the hub is connected by several hinge groups, and suspend in the elastic outer ring. When the vertical force acts on the hub, the hinges on the top and the sides are stretched, causing an elliptic deformation of the elastic outer ring. The hinge sets at the bottom of flexible road wheel are bent and in a free state. In the rolling condition, since the hub connected to the axle is in a suspended state, thus the impact caused by bumps, foreign objects or raised steps from the road can't be directly transmitted to the axle. The suspension bearing mode of flexible road wheel not only has good buffer damping function, but also improves the adhesion performance between the road wheel and track.

3. FINITE ELEMENT MODEL OF RIGID AND FLEXIBLE ROAD WHEEL

3.1 Geometric Model

The rigid road wheel is general composed of a steel solid wheel and the rubber layer wrapped the rim. The flexible road wheel is essentially different from the traditional rigid road wheel in structure, and is assembled from individual parts and realises the movement by the interaction between the individual parts. In order to improve the efficiency of modelling and solving, the rigid and flexible road wheel need to be reasonably simplified without affecting the function of each component. All round holes and chamfering are removed. The complex hinge set is reduced to a 3-link structure. The elastic ring twined by steel wire is simplified as a ring with rectangular section. All components of the rigid and flexible road wheel are built in the 3D modelling software CATIA.

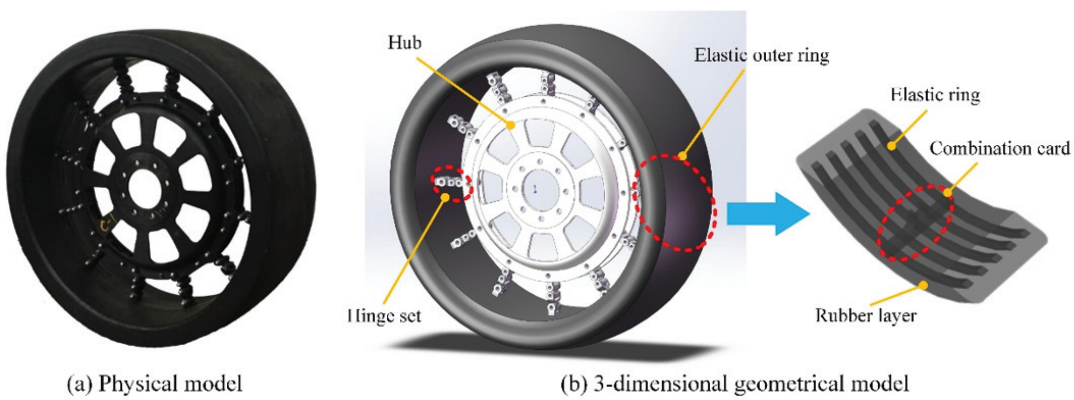


Figure 1. Structure of flexible road wheel.

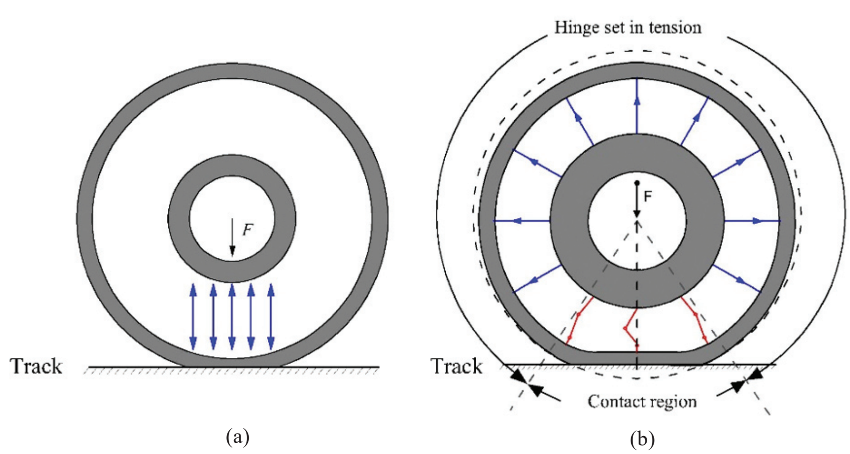


Figure 2. Load-bearing modes of the (a) Bottom bearing mode and (b) Suspension bearing mode.

3.2 Material Properties and Meshing

The detail three-dimensional nonlinear finite element (FE) models of the rigid road wheel and flexible road wheel were developed in ABAQUS/Standard. The material of the rigid and flexible road wheel includes rubber, spring steel and alloy steel. The mechanical property of rubber material is simulated by Mooney-Rivlin constitutive model, which have been widely used in engineering[9]. This model has been implemented into ABAQUS, and its strain energy density W can be written as[8]:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \quad (1)$$

The rubber material coefficients C_{10} and C_{01} in Mooney-Rivlin model can be determined by fitting the axial tensile test data. The rubber layer, hinge groups and suspension hub were meshed by the reduced integral unit C3D8R. Finally, the established finite element models of the rigid and flexible road wheel contain 175788 elements and 224978 elements, respectively, as shown in Fig. 3. The material attributes of the rigid and flexible road wheels are as shown in the Table 1.

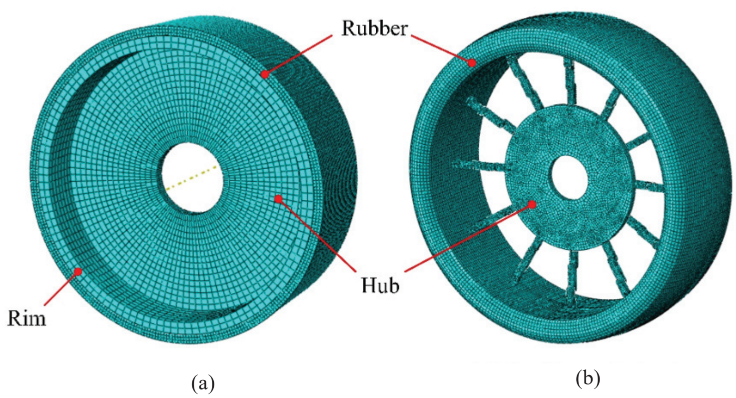


Figure 3. Finite element (FE) model of the (a) Rigid road wheel and (b) Flexible road wheel.

Table 1. Material attributes of rigid and flexible road wheel

Part	Density [kg/m³]	Young's modulus [MPa]	Poisson's ratio	C_{10}	C_{01}
Elastic ring	7.85×10^3	1.98×10^5	0.28	-	-
Hinge set	7.85×10^3	2.06×10^5	0.29		
Hub	7.85×10^3	2.12×10^5	0.32		
Rim	7.85×10^3	2.08×10^5	0.30		
Rubber	0.92×10^3	-	0.49	0.86	-0.19

3.3 Constraint Loading

The constraint relationships of each components of the rigid and flexible road wheel are directly defined according to the actual physical prototype. For the rigid road wheel, the outer rubber is attached to the rim by a fixed restraint. For the flexible road wheel, the elastic ring, rubber layer and combination card are combined together by fixed restraints. The rotational motion between two hinges, hinge and hub, and hinge and combination card are simulated by revolution pairs and the frictional action of the revolution pair is ignored. For ease of loading, all the degrees of freedom of the hub is coupled to a reference point, and the load is applied on it.

3.4 Model Validation

To ensure the accuracy of the numerical simulation, it is necessary to validate the finite element model of the rigid and flexible road wheel by static loading experiment. The static loading test was conducted by a self-developed vertical loading test bench to measure the radial sinking of the rigid and flexible road wheel under different vertical load[7]. Figure 4 shows that the squat of the rigid and flexible road wheel increases nonlinearly with an increase in the vertical load. Besides, the simulation results are in good agreement with the measured results, thus verifying the reliability of the established finite element (FE) model of flexible road wheel.

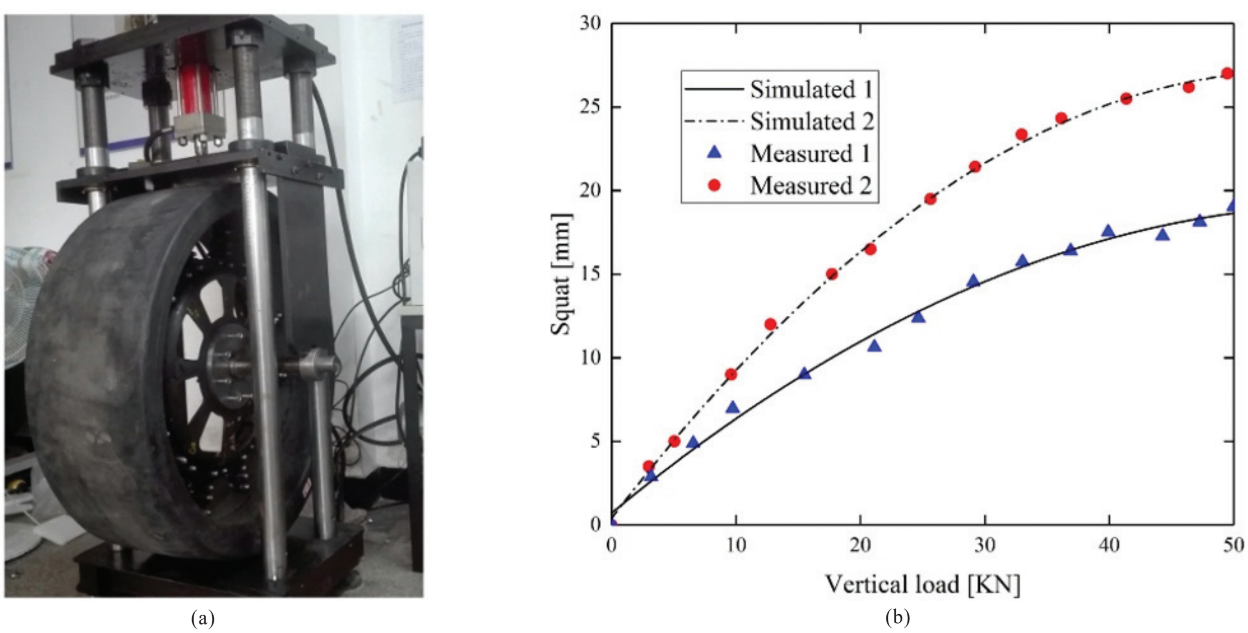


Figure 4. Static loading experiment of the rigid and flexible road wheel: (a) Test bench and (b) Squat varies with vertical load, 1-rigid road wheel and 2-flexible road wheel.

4. RESULTS ANALYSIS AND DISCUSSION

4.1 Stress and Deformation Analysis

Figure 5 shows the overall deformation cloud diagram of the rigid and flexible road wheel under a vertical load of 30 KN. As illustrated in Fig. 5(a), the overall deformation of the rigid road wheel is small, and the maximum deformation (2.99 mm) appears in the bottom rubber contacted with the track. It is because the bottom rubber is squeesed by the track plate and rim, but the rigidity of the rubber is much smaller than that of the rim and track. In the rolling state, the repeated extrusion deformation for a long time will cause the rapid rise in rubber temperature, accelerating the aging and destruction of the rubber material. As shown in Fig. 5(b), compared with the rigid road wheel, the overall deformation of the flexible road wheel is larger, but the force condition of the elastic outer ring is more uniform. The maximum deformation (5.69 mm) is located in the joint part of bottom hinge set.

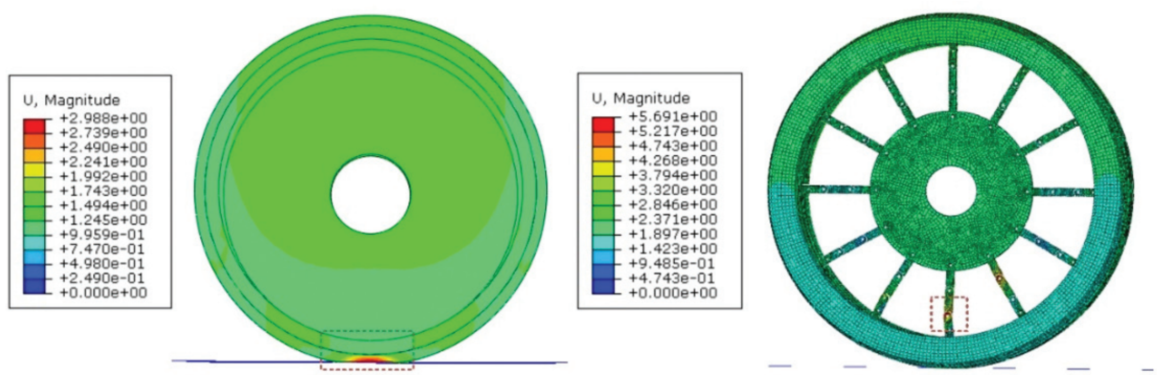
Figure 6 shows the overall equivalent stress distribution of the rigid road wheel and flexible road wheel under a vertical load of 30KN. As illustrated in Fig. 6, for the rigid road wheel, the high stress region lies in the bottom of the rim and extends outward, which verifies the bottom bearing mode of the rigid road wheel. The maximum equivalent stress of 19.76Mpa appears at the interface between the rim and rubber. For the flexible road wheel, the high stress region lies in the upper hinge sets, and the closer the hinge set is to the center position, the greater stress it is. The maximum equivalent stress of 47.82 Mpa appears in the joint part of the middle hinge set, which is the weakness of the flexible road wheel. The results of numerical analysis and the results of theoretical analysis are mutually verified.

4.2 Contact Analysis

Figure 7 shows the contact pressure distribution between the rigid and flexible road wheel and the track plate under the vertical load of 30KN. It can be seen from Fig. 7 that the length of the contact area of the rigid road wheel is larger than that of the flexible road wheel, while the width of the contact area of the rigid road wheel is smaller than that of the flexible road wheel. Besides, the maximum contact pressure of the rigid road wheel is greater than that of the flexible road wheel. This phenomenon is mainly due to the difference in load bearing mode. For the rigid road wheel, the bottom rubber is mainly extend along the width of the wheel, while for the flexible road wheel, the rubber is extended along the longitudinal direction to a certain extent, because of the elliptic deformation of the elastic outer ring. For quantitative analysis of contact pressure uniformity, we use the contact pressure skewness, which is defined as:

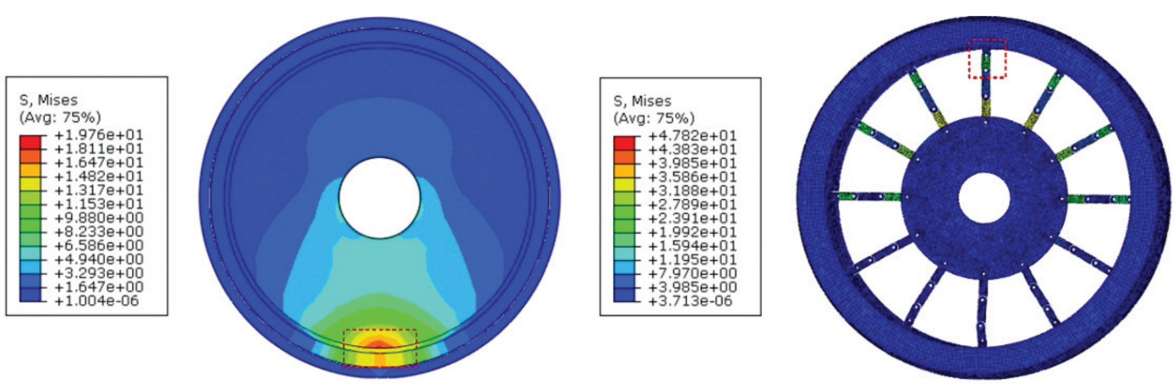
$$\alpha = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(p_i - \overline{p})^2} \tag{2}$$

where α is the contact pressure skewness; n is the number of measurement points; p_i is the pressure value of each measurement point; $\overline{p}$ is the average contact pressures. When the vertical load is 30KN, the contact pressure skewness of



(a) (b)

Figure 5. Overall deformation under the vertical load of 30KN of the (a) Rigid road wheel and (b) Flexible road wheel.



(a) (b)

Figure 6. Overall stress distribution under the vertical load of 30KN of the (a) Rigid road wheel and (b) Flexible road wheel.

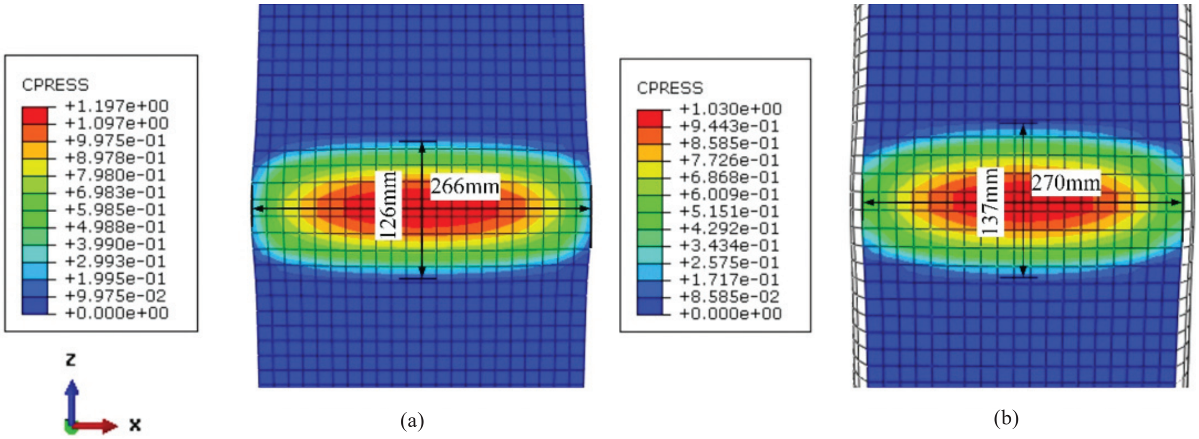


Figure 7. Contact pressure distribution under the vertical load of 30 Kn between the (a) Rigid road wheel and (b) Flexible road wheel and track plate.

the rigid and flexible road wheel are calculated to be 0.65MPa and 0.58MPa, respectively, indicating the contact pressure uniformity of flexible road wheel is better than that of the rigid road wheel.

4.3 Effect of Vertical Load

To study the influence of vertical load on the maximum stress and deformation of the rigid and flexible road wheel, the static loading performance of the rigid and flexible road wheel under different vertical loads was simulated. Figure 8 shows the variation trend between the maximum stress and deformation of the rigid and flexible road wheel and the vertical load. As shown in Fig. 8, the maximum stress and deformation of the rigid road wheel and flexible road wheel increase with an increase in vertical load. Compared with the rigid road wheel, the maximum stress and deformation of the flexible road wheel are more affected by the change in vertical load. This is mainly related to the structure and number of the hinge set, the structural optimisation and the increase in the number will contribute to the uniformity of the force of the flexible road wheel.

5. CONCLUSIONS

In this work, a new type of flexible road wheel, which has a unique suspension bearing mode with a high load-bearing efficiency and good wheel-track contact characteristics, is introduced. A finite element analysis method for numerical investigation of static loading performance of rigid and flexible road wheel is presented. This method can effectively analyse the internal stress of the rigid and flexible road wheels, shorten the cycle of design and analysis, and reduce the design cost. The finite element (FE) model of the road wheel considering the triple nonlinearity of structure, material and contact is established and verified by static loading test. The stress, deformation and contact characteristic of the rigid and flexible road wheels under static loading condition are compared and analysed. In addition, the influence of vertical load on maximum stress and deformation is also studied. The research results show that the contact uniformity of the flexible road wheel is better than that of the rigid road wheel under the static loading condition, but the maximum stress and deformation of the flexible road wheel are greater than that of the rigid road wheel. In the future study, we will further improve the

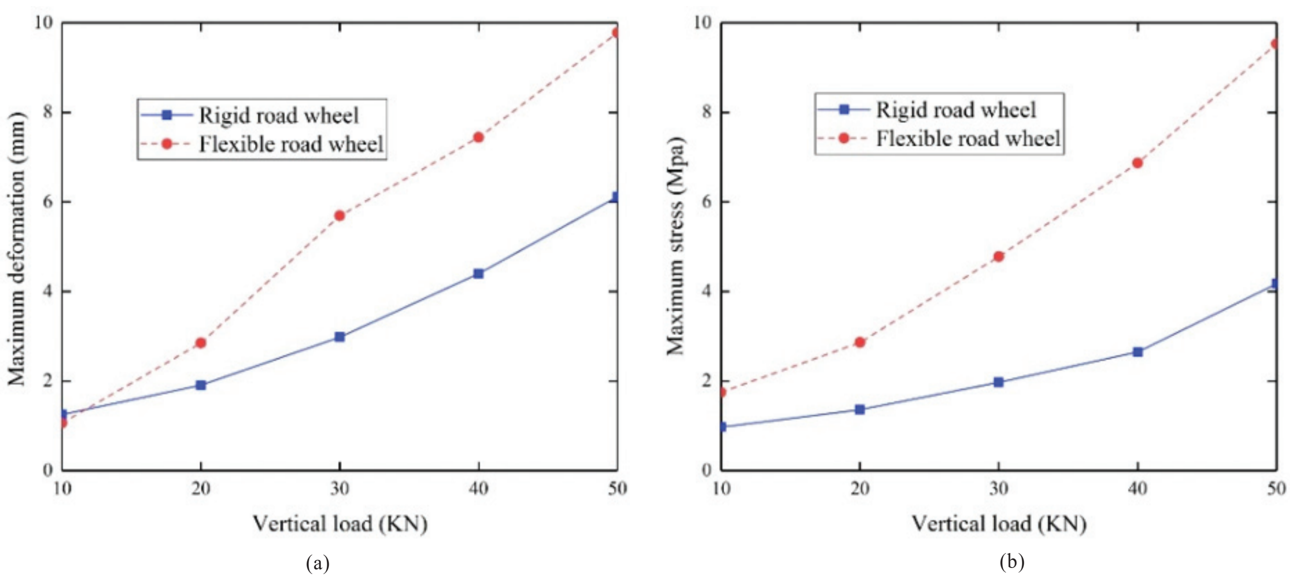


Figure 8. Maximum stress and deformation of (a) Rigid road wheel and (b) Flexible road wheel, increase with an increase in vertical load vertical load.

stress concentration phenomenon of the flexible road wheel by changing the number of the hinge sets and optimising its structure.

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