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Study on Static Load Mechanical Properties of Diamond Flexible Spoke Non-pneumatic Wheel

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***Abstract* – A kind of non pneumatic wheel with flexible diamond spoke structure and rubber tread bonded by polyurethane material is proposed. The static load-carrying characteristics and grounding characteristics of the non pneumatic diamond spoke wheel are analyzed under static load condition by finite element software ABAQUS simulation analysis. According to the change of the number of elements and the thickness of the support plate, the influence of the number of elements and the thickness of the support plate on the load-carrying characteristics and the grounding characteristics of the wheel is explored. The research results will provide a certain basis for the structure design, performance test and optimization of non pneumatic wheels in the future.**

***Keywords* – Unit Structure, Number of Units, Bearing Characteristics, Grounding Characteristics, Settlement.**

I. Introduction

At present, more and more safety tires are used in the market. As a kind of non pneumatic tire with high safety, although the technology is not fully mature, it is not widely used in the market, but its prospect is very considerable. For a long time, the safety problems of pneumatic tire caused by tire burst, air leakage and insufficient tire pressure can not be ignored. Therefore, researchers put forward the concept of non pneumatic tire. The non pneumatic wheel abandons one of the important parts of the traditional wheel, the pneumatic tube, and introduces the integrated design of wheel and rim. The tire body is mainly composed of support plate and spokes. When the non pneumatic wheel is impacted by the load, it is necessary to ensure that its support structure has enough deformation to reduce the wheel vibration, ensure the rebound speed and improve the ride comfort of the vehicle Sitting comfort.

After the emergence of non pneumatic honeycomb tire [1] and Michelin tweel [2], researchers at home and abroad are trying to develop a non pneumatic wheel structure with both comfort and performance. Ju jaehyung [3] used ABAQUS to analyze the relationship between the radial wall thickness and the bearing capacity of honeycomb tire, and designed a honeycomb structure with high fatigue resistance. Zhao Peng of Beijing University of chemical technology [4] used ABAQUS to study the tire's grounding performance and radial stiffness under static load, steady-state rolling and other conditions, which laid a foundation for the research of non pneumatic wheel. Kucewicz et al. [5] carried out vertical static deflection simulation test on tweel and honeycomb tire, and analyzed the influence of vertical displacement of hub, tread deformation and grounding pressure on the geometry of flexible spoke structure. Ganniari Papageorgiou [6] and others evaluated and optimized the load-carrying performance of honeycomb tire by changing various structural design parameters; Meng [7] and others established non pneumatic tire structures with different inner support structures and carried out static mechanical simulation experiments. According to the radial deformation, it shows that the inner support structure unit is cross arc unit and rectangular unit structure, which is more suitable for the design of non pneumatic wheel structure the plan. The structural parameters (geometric parameters and material parameters) of the tire also have a certain influence on the load-carrying capacity of the tire. Jin et al. [8] constructed a numerical model of non pneumatic tire with different geometric parameters but the same cell wall thickness or bearing capacity, and studied the effects of geometric parameters on the stress distribution, bearing capacity and rolling resistance of non pneumatic tire. Shashavali et al. [9] compared and analyzed the effects of nylon 4-6 and NBR on the mechanical properties of non pneumatic tire based on static structure analysis and modal analysis. The driving force and braking force are transmitted through the contact between the tread and the ground during driving. Different sinkage will have different ground pressure and ground area. The load bearing characteristics directly affect the ground performance of the tire. Zang Liguo et al. [10] compared and analyzed the grounding pressure distribution of pneumatic safety tire and mechanical elastic wheel under different loads through static grounding characteristic test. Throughout the above research, it can be seen that the bearing deformation design of tire is very important.

In this paper, the diamond flexible spoke non inflatable wheel structure is designed, the unit structure models with different densities and the wheel models with different support plate thickness are established, and the finite element analysis software ABAQUS is used to analyze the grounding pressure, support plate stress and wheel sinkage under static load conditions, so as to provide a reasonable scientific basis for the subsequent design of non inflatable wheel.

II. Introduction of non Pneumatic Wheel with Rhombic Flexible Spoke Structure

The diamond flexible spoke inflatable free wheel support plate is mainly composed of diamond unit body structure and circular array by element configuration method. According to 195 / 50R16 radial tire, the basic structural parameters of diamond flexible spoke non pneumatic wheel are as follows: outer diameter 602mm; section width 195mm; section height 97.5mm; rim 16in. The non pneumatic wheel structure chooses the number of its array according to the angle of the unit body to change the density of the unit body, and selects the appropriate unit body density according to the simulation results and performance requirements. The diamond shaped flexible spoke inflatable free wheel is composed of high-performance rubber tread, diamond shaped polyurethane support structure and aluminum alloy wheel hub. For the convenience of calculation, the tread pattern is simplified without affecting the results. The results of each parameter size and three-dimensional model are shown in the following figure:

Table 1. Parameter setting of flexible spoke non inflatable grid wheel.

Parameter Name	Size
Internal diameter/mm	200
External diameter/mm	301
Tire width/mm	195
Tread thickness/mm	16
Thickness of inner ring/mm	6

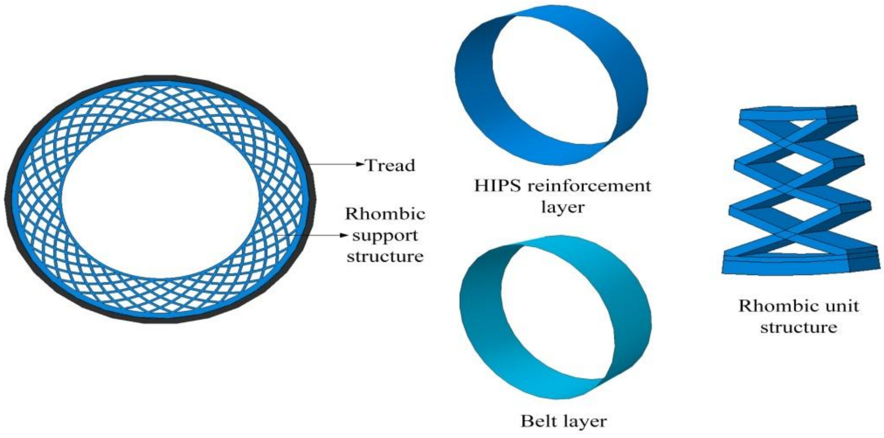

Fig. 1. Structure diagram of diamond flexible spoke non pneumatic wheel.

Diamond polyurethane support structure is the main component of non pneumatic wheel bearing. Diamond unit angle and diamond web thickness are the key mechanical parameters that affect the bearing performance of the whole wheel structure. The main work of this paper is to explore the variation of wheel bearing performance with the key structural mechanical parameters. Firstly, the angle of unit body is set to 10 degrees, that is, there are 36 ring arrays of diamond unit body structure. The thickness of diamond web plate is changed, and the web plate thickness is set to 5mm, 6mm and 7mm. Three kinds of non pneumatic wheel structures with different thickness of diamond web plate are defined as structures a, B and C respectively. The thickness of the diamond web plate is set to a fixed value of 5mm, and the structural angles of the diamond unit body are changed to 15 °, 12 ° and 10 ° respectively. The structures of the non pneumatic tire with the density of the diamond unit array of 24, 30 and 36 are defined as structures D, e and F. The structure parameters of the six structures are shown in Table 2, and the structure diagram is shown in Figure 2.

Table 2. Different structural parameters.

Type / Parameter	Structure A	Structure B	Structure C	Structure D	Structure E	Structure F
Thickness of support plate/mm	5mm	5mm	5mm	5mm	6mm	7mm
Array density/individual	24	30	36	36	36	36

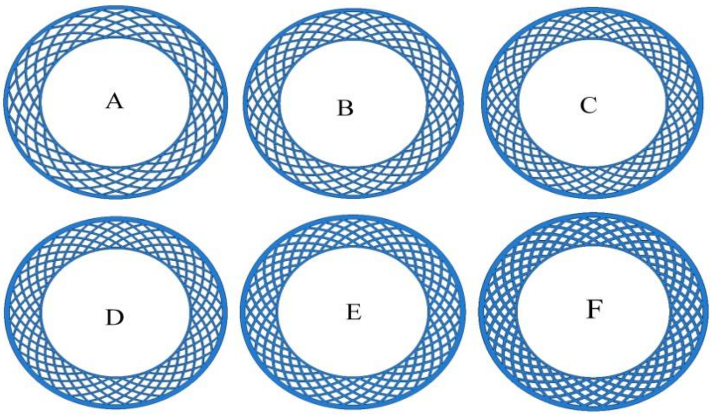

Fig. 2. Six types of diamond flexible spoke non pneumatic wheel structures.

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III. ESTABLISHMENT OF FINITE ELEMENT MODEL

A. *Material Model*

Diamond flexible spoke non pneumatic wheel is mainly composed of diamond flexible spoke tire body, tread with pattern and aluminum alloy wheel hub. The overall structural material is mainly super elastic polyurethane, which has low modulus, high hardness, high strength, high elongation, high bearing capacity, and good damping effect, so it is an ideal material for non pneumatic wheel materials. In this model, the ground is set as a rigid body, the hub is coupled with the inner surface of the flexible spoke structure, the diamond flexible spoke structure is made of polyurethane elastomer, and the rubber material of the tread can be regarded as an incompressible super elastomer. Therefore, the Mooney Rivlin model [11] is adopted to simulate the mechanical properties of the material, and the strain energy function is:

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

Where W is the strain energy; C_{01}, and C_{01} are the material constants obtained by experiments. The model is polyurethane elastomer with density of 1.2e-9kg/mm ^ 3, Young's modulus of 130MPa and Poisson's ratio of 0.4; the ground is simulated by rigid material with density of 7.9e-9kg/mm ^ 3, Young's modulus of 206000n / mm ^ 2 and Poisson's ratio of 0.3.l; I_1 is the first invariant of strain, I_2 is the second invariant of strain.

B. *Meshing*

Fully considering the incompressibility of tread rubber, the nonlinear problem of non pneumatic wheel in contact with the ground and the large deformation of diamond flexible spoke support plate structure, the 8-node fully integrated constant pressure hybrid hexahedral structural element (c3d8h) was selected as the tread rubber material; The diamond flexible spoke structure will produce large deformation under load, and the mesh will also be distorted. The accuracy of the 8-node hexahedral reduced integral solid element (c3d8r) will not be greatly affected when the mesh is distorted. Therefore, the diamond flexible spoke structure adopts c3d8r, and the enhanced “hourglass” control is selected; the deformation of the rim part is relatively small therefore, the rim connected by the diamond flexible spoke structure adopts the ten node quadrilateral tetrahedron element (c3d10). The main purpose of this paper is to study the load-bearing performance and grounding performance of diamond flexible spoke non pneumatic wheel, so in order to simplify the calculation, the tread pattern can be ignored.

C. *Boundary Conditions and Load Application*

In the contact process of the model, the rim and the inner surface of the diamond flexible spoke structure are coupled by tie constraints, and the tread is also bound with the diamond flexible spoke structure. The ground and rim are defined as rigid bodies, and the wheel and ground are frictional contact with each other. The friction coefficient is 0.5. The inner surface of the flexible spoke wheel is coupled with the central reference point, and a vertical downward load of 4000 n is applied at the central reference point. The load-carrying characteristics and grounding performance of the diamond flexible spoke non pneumatic wheel are analyzed under different number of units and different thickness of the spoke plate.

IV. Analysis of Simulation Results of Finites Element Model

A. *Subsidence Analysis*

In this section, by changing the thickness of the web plate and the density of the diamond element array, the variation law of the subsidence under the same load under the static load condition is analyzed. Keep the density of the array unchanged, set the thickness of the diamond plate to 5mm, 6mm, 7mm; keep the thickness of the diamond plate unchanged, set the density of the diamond unit array to 24, 30, 36. The analysis of simulation results is shown in Fig 3:

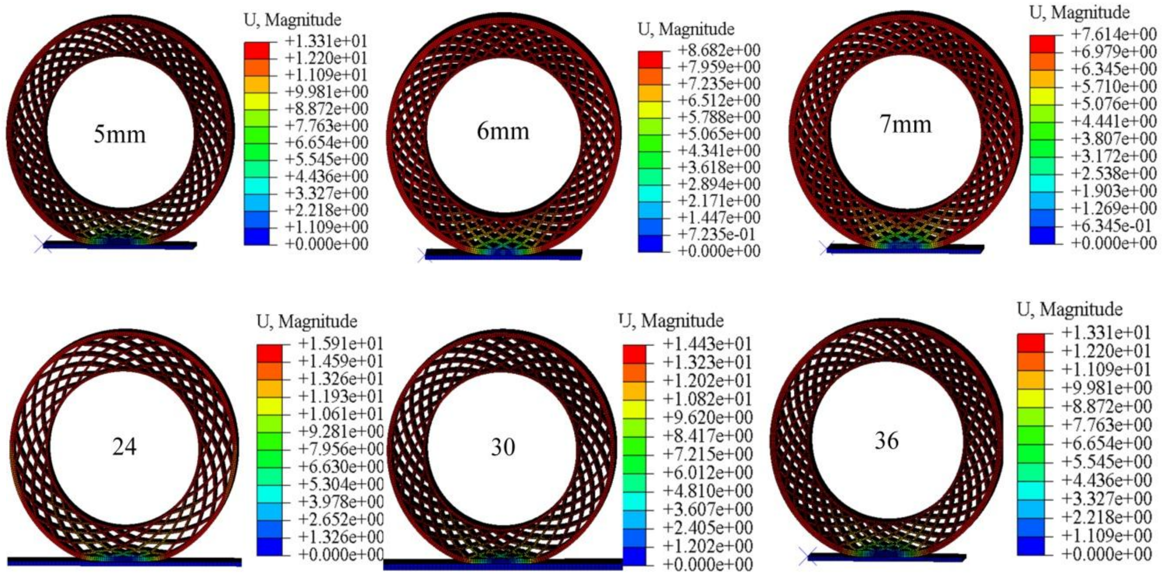
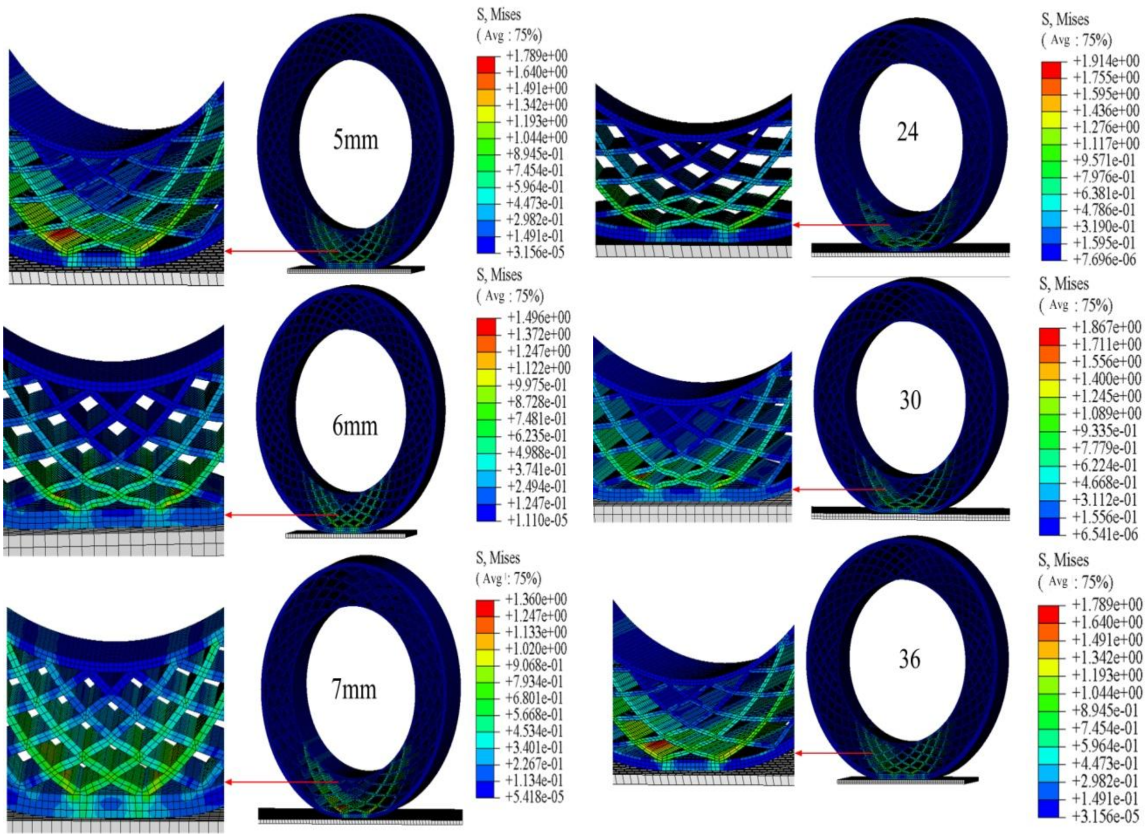


Fig. 3. Subsidence simulation results.

The reference model of the diamond flexible spoke non-pneumatic wheel structure is 195 / 50R16 radial tire. When the thickness of the diamond web is 5mm, the sinking is 13.31mm; when the thickness of the web is 6mm, the sinking is 8.682mm; when the thickness of the web is 7mm, the sinking is 7.614mm. With the increase of the thickness of the web plate, the settlement decreases obviously, and the difference of the settlement is large. The results show that the overall load-carrying capacity of the non-pneumatic wheel increases with the increase of the thickness of the support plate. Therefore, in the structural design, it can be considered to appropriately increase the web thickness to improve the overall bearing capacity of the wheel. When the thickness of the spoke plate increases, the load-carrying capacity of the flexible spoke non pneumatic wheel is obviously improved. With the increasing density of diamond element array, the load-carrying performance of flexible spoke non pneumatic wheel is also improving. When the density of diamond structure element array increases, the space of diamond structure cavity becomes smaller, and the number of diamond web plate increases, that is, the number of supporting structure increases, so the bearing capacity will be improved accordingly.

B. *Stress Analysis of Diamond Support*

In this section, keep the density of the diamond unit of the non inflatable wheel unchanged, change the thickness of the support plate to 5mm, 6mm and 7mm respectively, and load 4000N vertical load through the coupling center of the non inflatable wheel. The structural stress of the diamond support body is shown in Fig 4 (a); Keep the thickness of the support plate unchanged, change the array density of the diamond unit body, take the number of unit bodies as 24, 30 and 36 as examples to carry out simulation analysis and calculation, and the analysis results are shown in Fig 4 (b):



(a) The thickness of diamond web is different.   (b) The density of diamond element array is different.

Fig. 4. Contact patch of two tires under different loads.

When the inner support bears the load, the inner support should bear the force evenly, and the local maximum Mises should be as small as possible, so as to effectively improve the fatigue life of the wheel. By changing the thickness of the diamond web plate and the density of the diamond element array, the stress of the support plate of the diamond support plate structure under the static load condition is shown in the figure above. It can be seen from Fig. 4 (a) that when the thickness of the diamond web plate increases, the Mises stress of the diamond support structure is gradually decreasing, and the stress distribution tends to be more uniform, the results show that the load-bearing area of the support is relatively uniform, and there is no obvious local stress state, which improves the fatigue life of the non-pneumatic wheel to a certain extent. The stress concentration mainly occurs at the intersection of diamond support plate and web plate, and the possibility of damage at the stress concentration is relatively high. Fig. 4 (b) Mises stress of support plate decreases with the increasing density of diamond element array. The stress concentration point of diamond support structure occurs at the intersection of spokes near the tread area, and the stress distribution is relatively uniform at the rest of spokes. In the case of high stress, the supporting plates on both sides are partially warped, which affects the service life. According to the above results, the thickness of the web plate of the support structure and the array density of the support unit should be appropriately increased at the time of the design of the non pneumatic wheel, so as to improve the load-carrying performance of the whole non pneumatic wheel.

C. *Analysis of Grounding Characteristics*

When the load of the diamond flexible spoke non inflatable wheel is 4000N under the static load condition, the grounding marks are changed when the thickness of the diamond spoke plate and the density of the diamond unit array are changed, as shown in Fig 5.

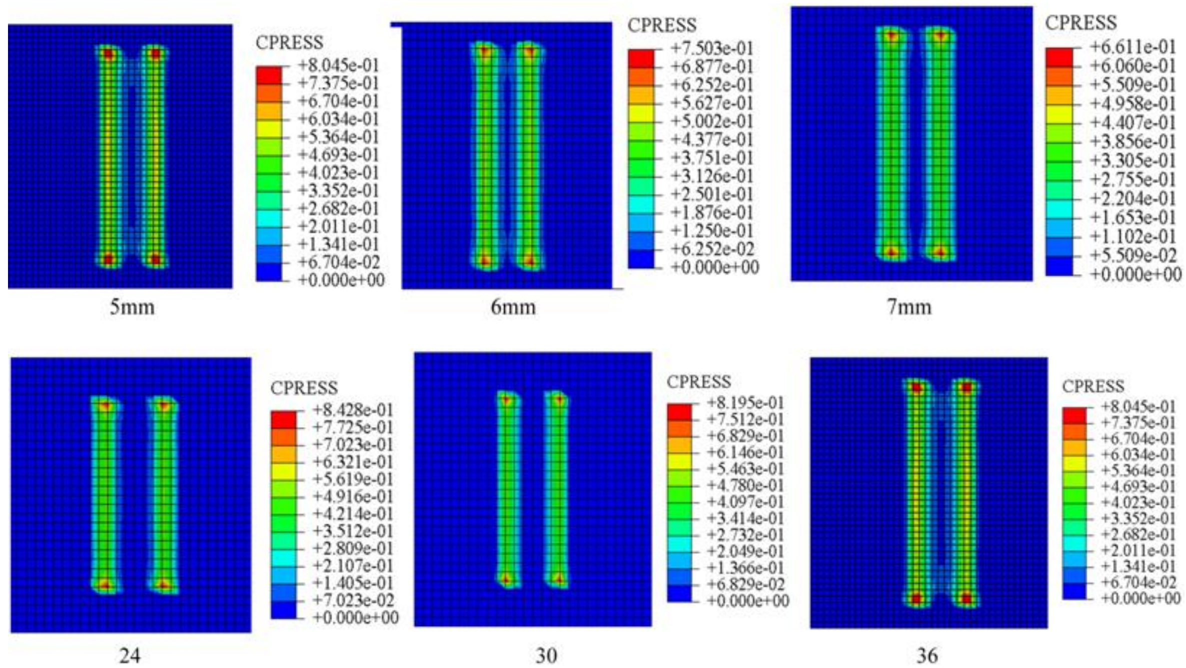


Fig. 5. The results of six kinds of static bearing grounding marks.

V. CONCLUSION

A. Compared with the same type of pneumatic tire, the sinkage of the rhombic flexible spoke non pneumatic wheel structure is similar, and the sinkage of the non pneumatic wheel structure also conforms to the sinkage standard of the type of pneumatic tire, and its bearing performance is better than that of the same type of pneumatic tire.

B. When the thickness of web plate and the density of rhombic element array are changed, the variation law of settlement is similar, and the bearing capacity increases with the increase of the thickness of web plate and the density of rhombic element array.

C. When the flexible spoke non pneumatic wheel structure is under static loading, the stress distribution of its support plate is relatively uniform, and the stress concentration phenomenon is not obvious, which reduces the possibility of fracture failure of the support plate structure due to stress concentration, and improves the overall service life of the wheel to a certain extent.

D. The results show that the grounding pressure decreases with the increase of load-carrying capacity, the grounding imprint presents a rectangular shape, and the distribution of grounding pressure is relatively uniform, which reduces the tread wear to a certain extent.

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