

Research Article

A Fatigue Evaluation Method for Radial Tire Based on Strain Energy Density Gradient

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Received 28 June 2020; Revised 8 February 2021; Accepted 25 February 2021; Published 5 March 2021

Academic Editor: Davide Palumbo

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Vehicle tires are major components that are subjected to fatigue loading and their durability is of economic interest as it is directly related to the safety of property and the life of producers and consumers. Tire durability is also a major issue of energy conservation and environmental protection. This research aims to establish a reasonable fatigue evaluation and optimization method that effectively improves tire fatigue life. In the study, 11.00R20 and 12.00R20 all-steel radial truck tires were the research objects, and the guiding hypothesis for the research was that “the maximum area of the strain energy density gradient modulus corresponds to the initial failure area, its direction corresponds to the crack propagation direction, and also the maximum strain energy value is inversely proportional to the tire fatigue life.” Through finite element analysis and durability test, the strain energy density gradient was determined as tire fatigue evaluation index, and the hypothesis of tire fatigue life prediction was validated. At the same time, the sensitivities of strain energy gradient to the tire structure parameters were calculated. Besides, the relationship between the structure parameters and the fatigue life was as well established in this paper. This study has formulated a tire fatigue evaluation method and proposed an effective optimization method for enhancing tire fatigue life. The results obtained are of high application value in offering guidance for tire structural design and useful for refining the fatigue failure theory of truck radial tires and improving durability.

1. Introduction

The durability of TBR (Truck Bus Radial) tire is directly related to the economic benefits of tire producers, consumer satisfaction, and safety. At the same time, it is a major factor for energy saving and environmental protection [1]. Tire engineers, in line with the empirical standard tire fatigue failure test, usually use the drum test bench to understand and evaluate the durability of tire [2] but rely on a single test which is not a comprehensive evaluation of the durability of the tire. Aside, this approach does not provide enough flexibility in the tire structure design process, and the longer test time as well as high economic cost makes it unattractive.

Jin invented equipment and used it to estimate tire life, issue alarm signal for changing tire, according to the tire pressure and temperature, and tire location identification

[3]. J. Su invented an automobile tire life detection system, made up for the shortage of automobile tire life detection equipment [4]. GR. Li invented a tire pattern to improve the tire life, which can not only ensure the mileage of the tire but also effectively improve the heat dissipation performance, thereby improving the tire tread life [5]. Chen invented a method for evaluating the adhesion life of steel cord in radial tire and found the relationship between the content of elemental metals and the life of adhesion by chemical analysis so that the life of bonding force can be judged and provided the judgment basis for tire fault analysis [6]. Goku Shunsuke invented a tire carcass life prediction system for predicting the remaining tire carcass life against the carcass in the tire and predicted the remaining driving distance according to the tire internal pressure and temperature and the physical attribute value of the carcass structure component [7].

The fatigue life of the tire is composed of crack forming and crack propagation. At present, the strain energy density (SED) is used as the evaluation index of tire fatigue life and structural optimization at home and abroad, and the empirical formula for the tire life and strain energy density is established [8–13]. However, this method cannot predict the direction of crack propagation, and the empirical formula ignores the difference of tire structure, making it impractical; literature [14–19] uses the virtual crack closure technique (VCCT) based on fracture energy density or strain energy release rate to predict the crack propagation direction effectively, while it requires the initial crack, and the influence of the initial crack location on the calculation results cannot be ignored. Ebbott [20] first used VCCT for truck tire durability and Zhong [21] applied more complex fatigue and fracture treatments; SOUTH [22–26] studied the formation and propagation of cracks between two layers of rubber with cord and predicted the fatigue life by S–N test curve and finite element analysis (FEA). However, the fatigue life curve of the tire using S–N has a long test period and high cost, which limits its application; Liu Yuyan used the damage mechanics method while considering the loading frequency, mean stress, stress amplitude, and fatigue effect of the heating process on fatigue life [27–29] to establish the damage evolution equation and the fatigue life prediction equation of rubber composites; Tian Zhenhui of China Earthquake Administration Institute of engineering mechanics and Tan Huifeng et al. of Harbin Institute of Technology Composite materials research [30] conducted an experiment and found that the variation of the cyclic maximum strain of the double layer rubber composite with the cycle times follows the law of the three stages.

To sum up, there are many methods employed to study the fatigue failure of the tire, each has its own advantages and disadvantages, with the main problem being the limitations of each method and the vast discrepancy between study results and the actual fatigue failure phenomenon of the tire. The dimensionless parameter, strain energy density gradient (SEDG), has been successfully applied in the dam strength and earthquake prediction [31] and was used to predict the failure modulus and failure strength of concrete and geology, but it has not been reported in tire fatigue life analysis and prediction. In this paper, the TBR tires 11.00R20 and 12.00R20 are the research object. At the same time, the strain energy density gradient model was adopted to study the fatigue durability of the tire by calculating and describing the strain energy density distribution and gradient of the tire using finite element analysis and numerical analysis. The results show that the maximum value of strain energy density gradient corresponds to the initial failure zone, and its direction corresponds to the crack direction.

Tire designers usually employ the trial-and-error method to adjust the structure of the material parameters to improve tire durability. As a result, the design work is inefficient and expensive. In the literature [32], the sensitivity analysis of tire material was carried out to establish the relationship between tire fatigue life evaluation index and rubber material parameters with a focus on investigating the influence of different parameters on fatigue life.

The fatigue evaluation and sensitivity analysis proposed in this paper have the object of solving the failure strain energy density gradient sensitivity of structure parameters through seeking the most sensitive parameters of tire structure design in order to promote TBR tire fatigue durability by optimizing the sensitive parameters. According to the simulation results of tire performance, the tire production process was adjusted; the test tire was then produced after which a durability test was carried out. The experimental results show that the optimized scheme can significantly improve the fatigue life of the tire, which proved that the proposed method in this paper is feasible to evaluate and predict the durability of the tire. A simple process chart for the test and analysis carried out in the paper and their purpose is shown in Figure 1.

2. Tire Durability Test

In this study, the tire durability test was carried out using the tire fatigue durability tester. A real fatigue test stand with a mounted tire is shown in Figure 2. The TBR tires 11.00R20 and 12.00R20 are the test tire. The tire test conditions are usually harsh conditions such that the applied load is twice the rated load value of the tire. These harshly applied conditions are used in order to shorten the test time and save the cost of the trial process [33]. Refer to Table 1, for the details of the harshly applied conditions.

At the end of the experiment, the tire sections were cut for subsequent modeling and analysis. A total of five (5) 11.00R20, eight (8) 12.00R20, and two (2) 255/70R22.5 tires were subjected to the fatigue endurance test. By observing the failure forms of each tire, it was found that the specific failure parts and the direction of crack propagation are different, yet the failure mode is mainly composed of tire bead and shoulder crack, indicating that it is difficult to study the fatigue durability of tire by the VCCT method. However, this method needs to set the initial crack during tire modeling. It is difficult to match the actual failure forms of the tire with the tire model. At the same time, this will take a lot of time, so this method is not used in this article.

The section of a test tire is shown in Figure 3, while Table 1 shows the main failure forms of tires and test results.

As shown in Table 1, in order to further prove the effectiveness of the proposed fatigue evaluation using the SEDG method, the above process is repeated for each test tire to verify whether the initial failure location and crack direction obtained by the method are consistent with the actual damage form. The main failure forms of tires are left bead area crack, right bead area crack, right shoulder area crack, left and right bead areas crack, and right bead area crack.

3. The FE Model

There are lots of approaches mentioned in research on how to build tire FE (finite element) model [34–39]. In order to obtain the actual structure of the tire, all the tires were cut after the durability test. The geometry of the tire is based on the test tire section cut from the tire wire cutter. After getting

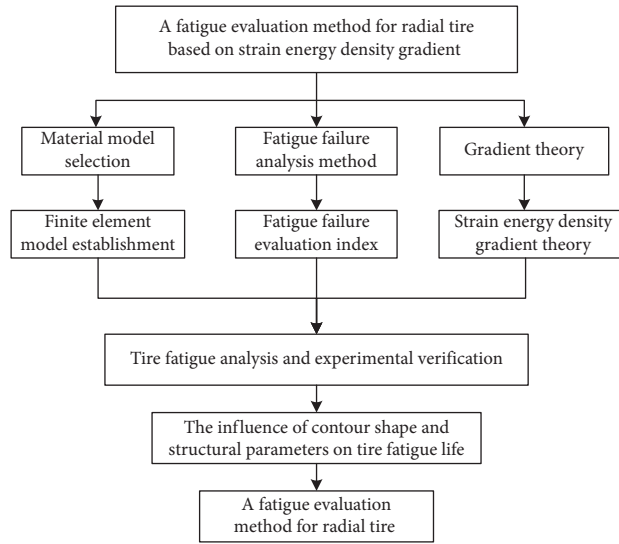


FIGURE 1: Flowchart.



FIGURE 2: Real fatigue test stand with a tire.

TABLE 1: Tire endurance test conditions and results summary.

Tire model	Number	Pressure (kPa)	Load (N)	Damage form	Life (h)
11.00R20	1	600	71000	Left bead area crack	40.17
	2	600	71000	Left bead area crack	44.45
	3	600	71000	Right bead area crack	60.12
12.00R20	1	830	75000	Right shoulder area crack	119.23
	2	830	75000	Right bead area crack	72.88
	3	830	75000	Left bead area crack	102.53
	4	830	75000	Right shoulder and bead areas crack	117.12
	5	830	75000	Left and right bead areas crack	107.7
	6	830	75000	Right bead area crack	58.02
255/70R22.5	1	830	25000	Right shoulder area crack	60
	2	830	25000	Not destroyed	100+

the tire section, we scan the tire section with a scanner and redraw it in AutoCAD to get the tire geometric model. Then, Hypermesh was applied to create the 2D FE model of the tire. The damaged part of the tire was refined to get an accuracy simulation result. The tire 2D FE model was imported to Abaqus and rotated by 360 degrees to form a 3D tire model. The 2D and 3D models are shown in Figure 4.

The uniform grid model is adopted and the whole 3D model is controlled around 294000 elements and 315000 nodes [40].

The tire is a composite of various materials, including rubber compounds, steel cord, and cord-rubber composite. As rubber is a hyperplastic material, YEOH material formulation is suitable for simulating nonlinear mechanical

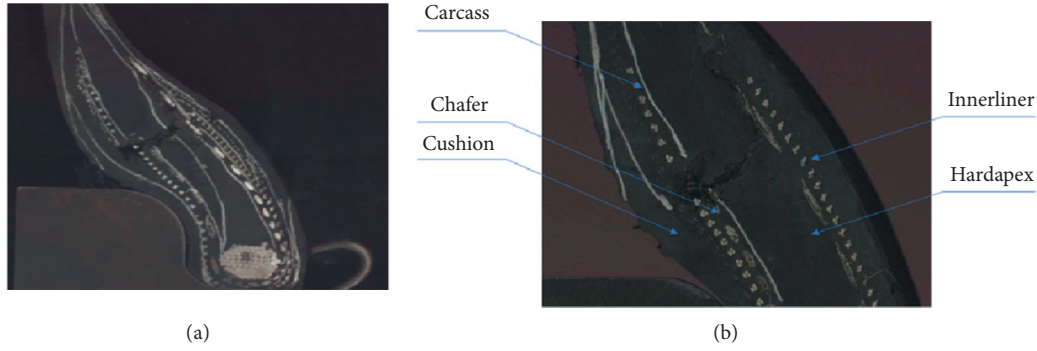


FIGURE 3: Section of sample test tire. (a) Tire bead area. (b) Failure point of the bead area.

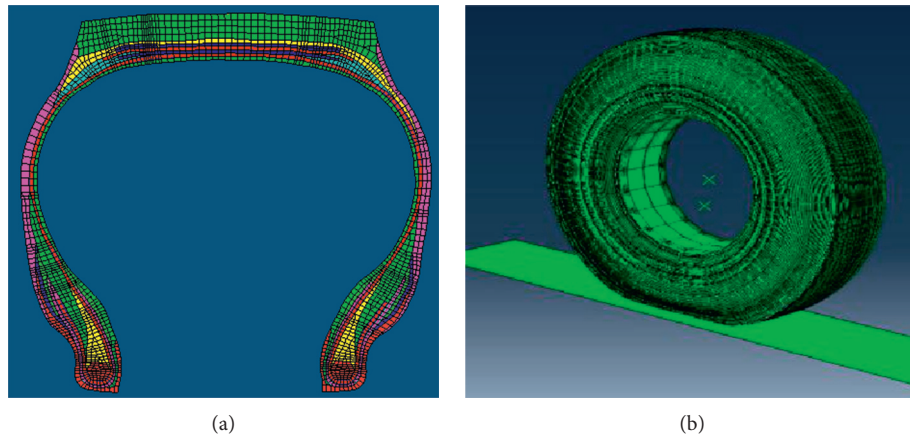


FIGURE 4: Finite element model. (a) Two-dimensional finite element model. (b) Three-dimensional finite element model.

behavior and incompressible property of the tire [41]. The reinforcement elements, usually called cords, are assumed to be linear elastic materials in this simulation. Rebar elements are selected to simulate the orthotropic elastic properties of the cord-rubber system [42].

The element type of CGAX4H and CGAX3H was selected to simulate the rubber material and the element type of SFGAX1 was selected for the tire cord part. The wheel rim and the road surface are defined as an analytical rigid body. The applied pressure and load are the same as the tire endurance test shown in Table 1.

4. Strain Energy Density Gradient

Based on the finite element model, the strain energy distribution (SED) can be calculated in Abaqus.

The SED value at a point (x,y) in any section of the tire can be described as two-element function $z=f(x,y)$. This function represents a surface geometry, and the equation of the equal height curve ι of the surface which is cut by the plane $z=c$ (C is constant) is

$$\begin{cases} z = f(x, y), \\ z = c. \end{cases} \quad (1)$$

The projection of the curve ι on the xOy surface is a plane curve L^* ; the equation in the xOy plane rectangular coordinate system is

$$f(x, y) = c. \quad (2)$$

For a point on the curve L^* , the function values that are given to the function are c , so we call the plane curve L^* as the contour of the function [43, 44]. The normal vector at the point $p(x,y)$ of the contour, namely, the gradient is

$$\frac{\partial f}{\partial x}i + \frac{\partial f}{\partial y}j. \quad (3)$$

As a result, at any point, the obtainable gradient direction of the function and normal direction of the contour line $f(x,y)=c$ over a point P have the same direction and point from the lower value of the contour to the higher contour. The modulus of the gradient is the maximum value of the derivative of the function at that point (directional derivative along this direction) and the module of strain energy density gradient (SEDG) is expressed as $|grad(x, y)|$.

From this, we know that the area with the maximum value of SEDG modulus is the biggest SED change amplitude. This proves that the above is the most frequent and intense area of energy storage and release. Based on fracture

mechanics theory, the crack growth rate is proportional to the strain energy release rate [45]. The dimensionless parameter gradient modulus is suitable for establishing the mathematical relationship with fatigue life. Therefore, SEDG can be used as the tire fatigue evaluation index, and the relationship between the index and the fatigue failure form and life of the tire can be established as the tire fatigue evaluation method proposed in this paper.

5. Analysis of Results

The contact center of the tire surface was selected in Abaqus such that the output node coordinates and the corresponding SED were of the (x, y, z) form, where x, y are the usual output node coordinates and z is for the coordinates of the SED value.

As shown in Figure 5, MATLAB programming was used to produce SED contour map and SEDG two-dimensional vector. The grid process was selected for Kriging interpolation. The advantages of this method are the overlap in the interpolation points and sampling points; the interpolation point value is the sampling point value and in order to maximize a representative sample. When there are a lot of data points, it is linear and unbiased and offers minimum estimation variance, making the result of interpolation more reliable [46, 47].

As can be seen from Figure 5, the SED concentration area is different from SEDG. Specifically, the concentration area originates and migrates from the shoulder and sidewall to the end of the belt, which is consistent with the fact that the main part of the damage of the shoulder is at the end of the belt. It is evident that the SEDG method is more accurate in predicting the damage site.

For example, the analysis process of using the fatigue section in Figure 3 can be as follows: the maximum values of SEDG modulus and their coordinates and directions for each part can be deduced by calculating and plotting the SEDG 2D vector of the left and right shoulder and bead, respectively. As shown in Figure 6, the maximum value of the SEDG modulus is at the left bead, and the direction angle is shown in Figure 6(c). As shown in Figure 7, in order to illustrate the feasibility of using SEDG to analyze the fatigue failure of the tire, the maximum value and direction of SEDG modulus in the tire finite element analysis model and the corresponding position of the tire section is marked.

From Figure 8, the initial failure location and the crack orientation determined by the SEDG method are consistent with the actual failure module. As shown in Figure 7, in this paper, in order to further prove the validity of the proposed method using SEDG for fatigue discrimination, the other 2 fatigue failure sections are analyzed in the same way. Thus, the direction of the SEDG corresponds with the direction of the fastest cyclical change; see Figures 7 and 9.

In Table 2, in order to verify whether the initial failure location and the crack propagation direction are consistent with the actual situation, the above process is repeated for each test section, and the coordinates, direction of crack propagation, and corresponding lifetime values are derived and presented as follows.

From Table 2, the coordinates of the maximum SEDG modulus correspond with the actual initial damage site. Apart from the gradient direction of 12.00R20-2 which is not consistent with the direction of crack angle, the rest are the same. Overall, there is an inverse relationship between the life span and the maximum gradient modulus, see Figure 9. It is indicated that the larger the gradient modulus, the shorter the lifetime. For that reason, tire fatigue can be evaluated by means of SEDG.

By means of the above analysis and the subsequent experimental verification, the position of this paper is that the SEDG method can be applied to predict and select the durability of each scheme in the design stage and to improve the durability test method and evaluation system in failure determination.

Then, the fatigue life test is performed, which generally meets that the crack is in the same direction as the gradient. In general, the fatigue life is inversely proportional to the maximum value of the gradient modulus; that is, the larger the maximum value of the gradient modulus, the shorter the life. Therefore, SEDG can be used to evaluate and predict tire fatigue failure forms and fatigue life.

6. Sensitivity Analysis of Structural Parameters

6.1. Structural Design. The role of SEDG in the design stage is mainly for the purpose of comparison and selection of optimization scheme, but designers are confronted with complex object structures, a variety of materials to choose from, so it is urgent to find the most effective and directional parameters, which when altered can significantly change the SEDG affecting tire durability and thereby ensuring work efficiency. In this paper, the main structural parameters of the vulnerable parts are adjusted to calculate the sensitivity of SEDG to these structural parameters and find out the parameters which have the greatest impact on SEDG and fatigue life. The specific structure design is shown in Table 3.

6.2. Sensitivity Analysis. Taking the change amplitude of the SEDG model as the objective function, the virtual work equation of finite deformation is taken as the constraint condition, respectively, expressed as

$$\Phi_r = \Phi_r(\alpha^t(h_p), \Delta u^N(h_p), h_p), \quad (4)$$

$$F^N = F^N(\alpha^t(h_p), \Delta u^N(h_p), h_p) = 0, \quad (5)$$

where h_p is the corresponding structural parameters, Φ_r is the corresponding SEDG modulus, $F^N = 0$ is the virtual work equation in the form of finite deformation increment, $\Delta u^N(h_p)$ is incremental displacement, and $\alpha^t(h_p)$ is the state of the moment t . The sensitivity of objective function and constraint equation to design variables can be obtained by formulas (4) and (5):

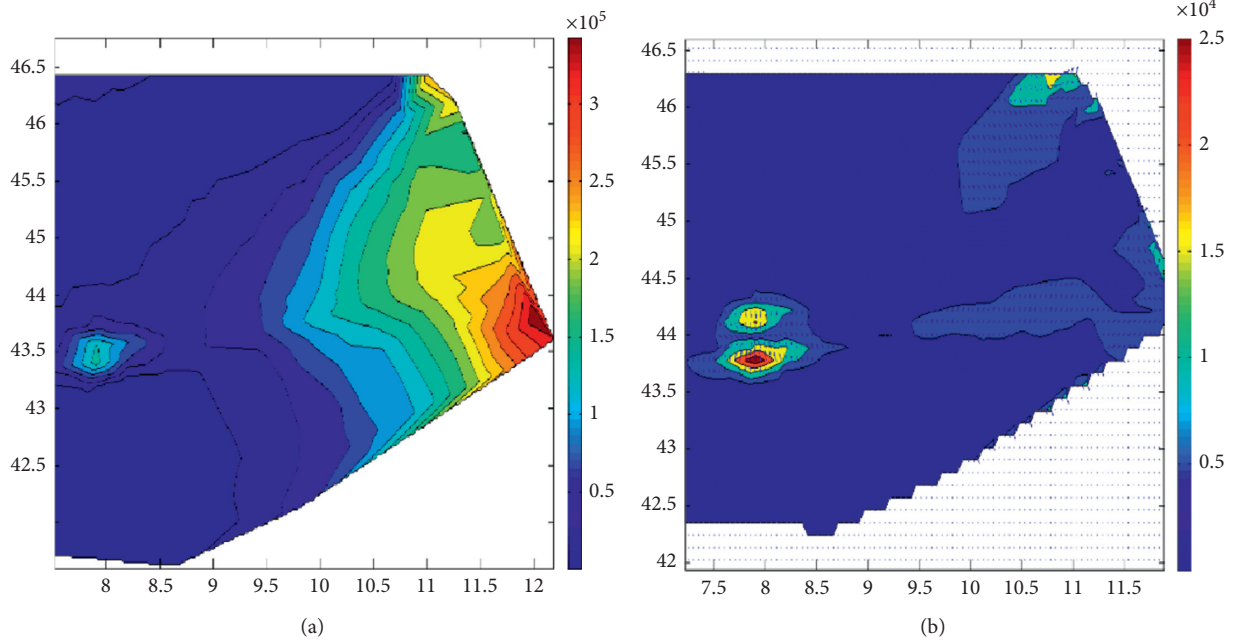


FIGURE 5: SED contour map and SEDG two-dimensional vector diagram of a shoulder. (a) SED contour map. (b) SEDG 2D vector map.

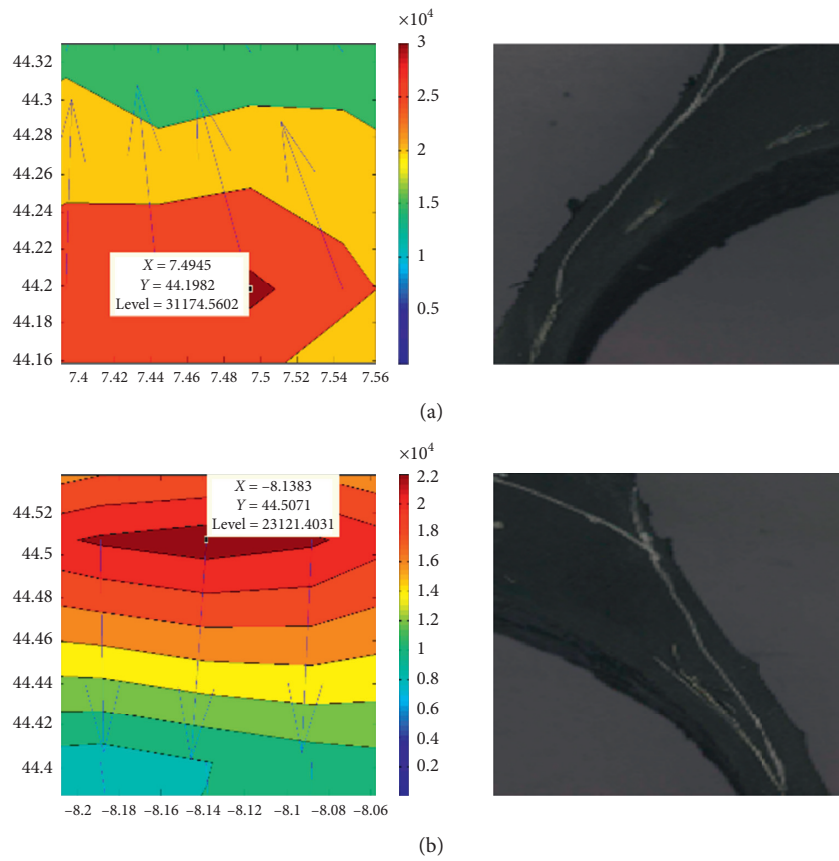


FIGURE 6: Continued.

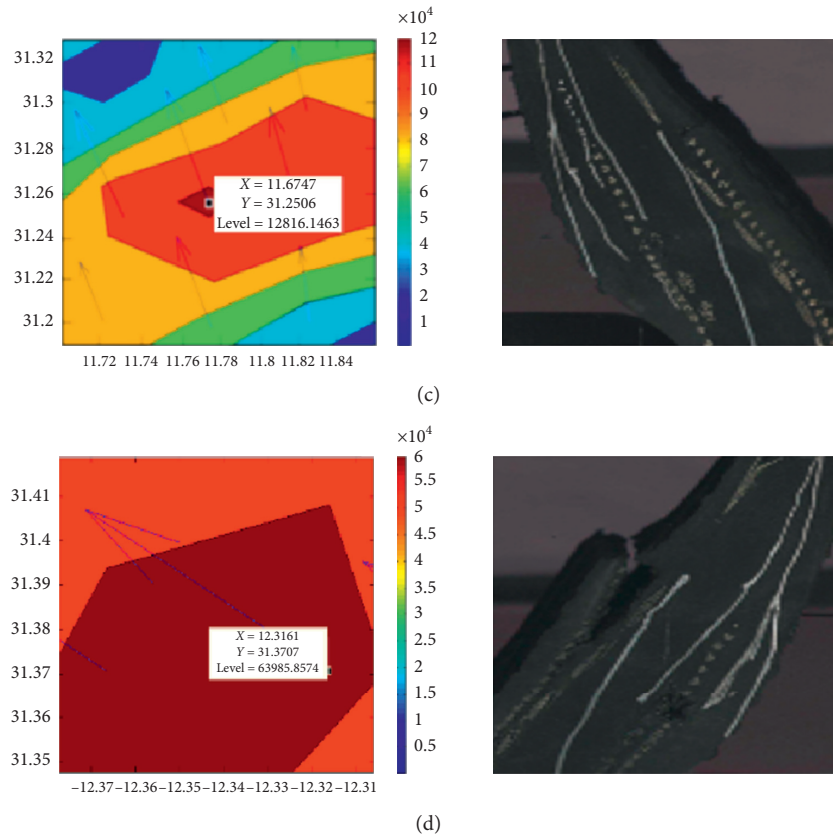


FIGURE 6: SEDG 2D vector of each part. (a) Left tire shoulder. (b) Right tire shoulder. (c) Left bead area. (d) Right bead area.

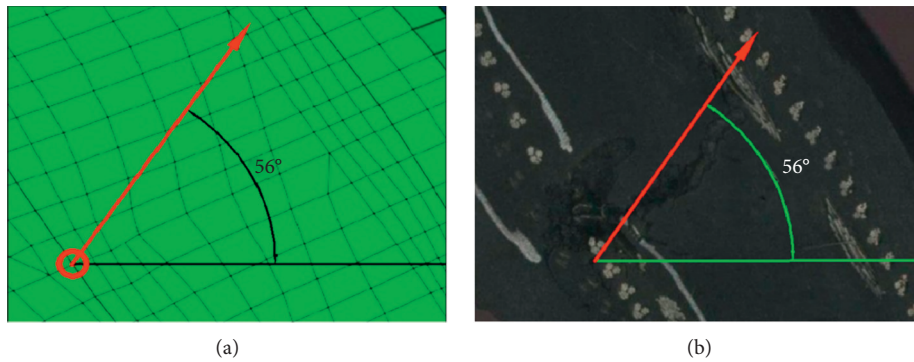


FIGURE 7: The concrete damage form of the other 2 sections: (a) analysis of fatigue Section 1 results; (b) analysis of fatigue Section 2 results.

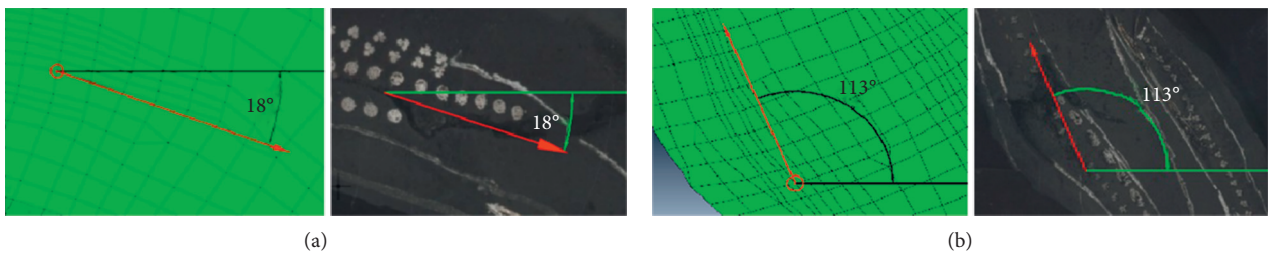


FIGURE 8: Concrete failure modulus. (a) Location of damage in Abaqus. (b) Failure form in the actual section. (a) Tire shoulder area. (b) Tire bead area.

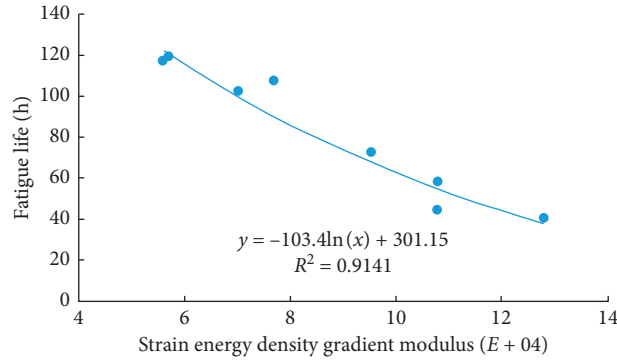


FIGURE 9: The fitting curves of tire fatigue life.

TABLE 2: Failure location and crack angle statistics.

Number	Gradient modulus (E4)	Coordinate	Crack angle	Correspond	Life (h)
11.00R20	1	(11.77,31.25)	56	Yes	40.17
	2	(11.83,31.87)	139	Yes	44.45
	3	(-11.20,31.19)	41	Yes	60.12
12.00R20	1	(-8.47,46.74)	18	Yes	119.23
	2	(-13.10,30.88)	83	Yes	72.88
	3	(12.80,30.67)	113	Yes	102.53
	4	(-8.71,46.64) (-12.48,30.69)	122	Yes	117.12
	5	(12.95,30.84) (-12.96,30.84)	56	Yes	
	6	(12.95,30.84) (-12.96,30.84)	57	Yes	107.7
	8.96	(11.95,30.59)	76	Yes	
	10.80	(11.95,30.59)	48	Yes	58.02

$$\frac{d\Phi_r}{dh_p} = \frac{\partial\Phi_r}{\partial h_p} + \frac{\partial\Phi_r}{\partial\alpha^t} \frac{d\alpha^t}{dh_p} + \frac{\partial\Phi_r}{\partial\Delta u^N} \frac{d\Delta u^N}{dh_p}, \quad (6)$$

$$\frac{dF^N}{dh_p} = \frac{\partial F^N}{\partial h_p} + \frac{\partial F^N}{\partial\alpha^t} \frac{d\alpha^t}{dh_p} + \frac{\partial F^N}{\partial\Delta u^N} \frac{d\Delta u^N}{dh_p} = 0. \quad (7)$$

The results of structural sensitivity analysis are shown in Table 4.

As can be seen from Table 4, due to the huge changes in sensitivity, the width of the 2# belt is more sensitive to the SEDG modulus at the shoulder and the height of carcass turn-up edge and steel wire strengthened layer height are the most sensitive parameter to bead SEDG modulus. The implication is that a change in the width of the 2# belt and the interlayer of the height of carcass turn-up edge and steel wire strengthened layer height can greatly influence the fatigue life of the tire shoulder and bead. Designers can focus on changing the structural parameters, as well as other material parameters in order to improve the SEDG distribution of the vulnerable area, so as to enhance the durability of the tire.

7. Trial Tire Production and Testing

As depicted in Figure 10, it is the current design of 11.00R20 with a maximum SEDG tire modulus of 90288, the scheme of the optimal solution with a value of 58766, and its material distribution map. Figure 10 refers to the height of the carcass bulge end and the reinforcement layer because the carcass bulge end and the reinforcement layer are more sensitive to the SEDG modulus at the bead, so changing the carcass height affects significantly the fatigue life at the tire shoulders and beads area.

Figure 11 is the failure section of the trial sample tire according to the optimization scheme, with the normal production of the tire, followed by durability testing, after which the damaged section was cut off. The experimental results show that the fatigue life of the current design is 45 hours, and the fatigue life of the optimized scheme is about 80 hours. The latter significantly improves the fatigue life of the tire. The experimental results show that the above-optimized scheme is effective; the reliability of the method is further verified. Figure 11 shows the tire cross sections of the current design and optimized design after the durability

TABLE 3: Structural sensitivity design.

Structure parameter	Scheme	Pressure (kPa)	Load (N)	Change
Current theoretical design section	1	600	71000	—
	2	600	71000	Add 10 mm
Steel wire strengthened layer height	3	600	71000	Add 18 mm
	4	600	71000	Add 28 mm
	5	600	71000	Reduce 4.5 mm
Height of carcass turn-up edge	6	600	71000	Reduce 13.5 mm
	7	600	71000	Reduce 22.5 mm
Four-layer belt structure	8	600	71000	Reduce 27 mm
	9	600	71000	—
	10	600	71000	Add 2.5 mm
	11	600	71000	Add 5 mm
The width of 2# belt	12	600	71000	Add 7.5 mm
	13	600	71000	Add 10 mm
	14	600	71000	Reduce 2.5 mm
	15	600	71000	Reduce 5 mm

TABLE 4: Results of structural sensitivity analysis.

Scheme	SEDG modulus of tire shoulder	Sensitivity	SEDG modulus of bead	Sensitivity
1	45741	—	90288	—
2	46009	26.8	101972	1168.4
3	39552	-343.8	81754	-474.1
4	41825	-139.9	65565	-882.9
5	46365	138.7	91750	324.9
6	47993	166.8	146225	4143.5
7	48757	134.0	82876	-329.4
8	38289	-276	87132	-116.9
9	31002	—	94021	—
10	32807	722	92447	-629.6
11	28919	-416.6	92439	-316.4
12	29115	-251.6	92429	-212.3
13	29651	-135.1	92413	-160.8
14	32555	621.2	92471	-620
15	32124	224.4	92511	-302

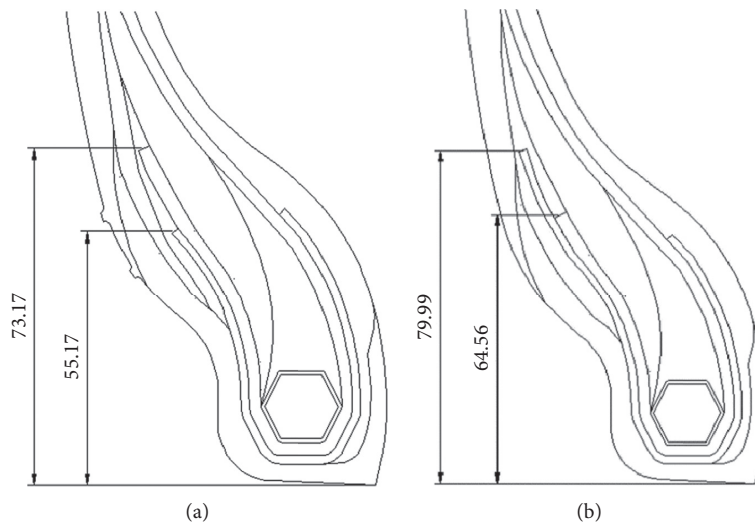


FIGURE 10: Current design and optimized design of tire material distribution map. (a) Current design. (b) Optimized design.

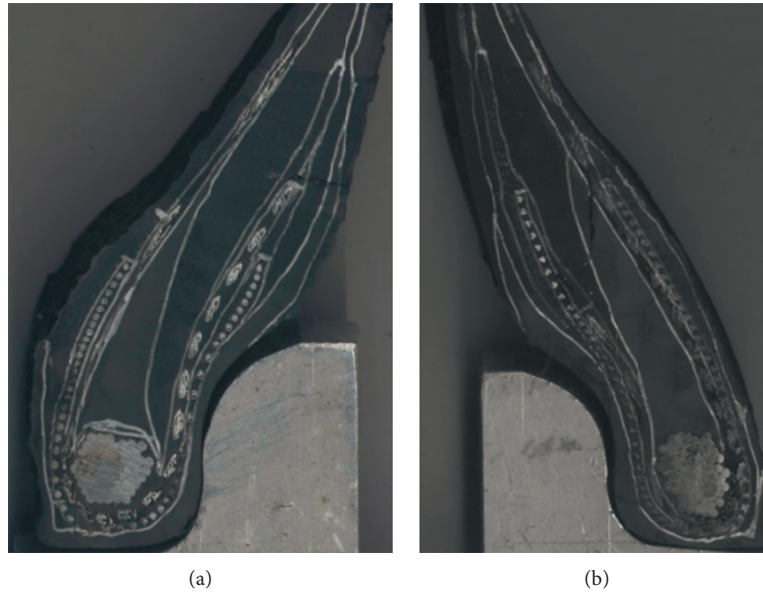


FIGURE 11: Fatigue failure section of current design and optimized design. (a) Current design. (b) Optimized design.

tests. The results show that the optimization scheme can significantly improve tire fatigue life, which not only proves the effectiveness of the above structural optimization method but also verifies the method of fatigue analysis, especially the accuracy of fatigue life prediction.

8. Conclusion

In this paper, the effectiveness of the gradient strain energy density in the fatigue failure and fatigue life prediction of the tire is discussed by means of finite element simulation and tire endurance test. The results show that the maximum value of the strain energy density gradient modulus corresponds to the initial failure zone, which is inversely proportional to the fatigue life of the tire, and is in the direction of crack propagation. On this basis, the sensitivity of the strain energy density gradient to the structural parameters is studied by utilizing the sensitivity analysis technique. The results showed that the width of the 2# belt is the most sensitive parameter to shoulder in SEDG modulus; the height of carcass turn-up edge and steel wire strengthened layer height and are most sensitive to bead SEDG modulus. It became obvious that changing the structural parameters will have a great impact on the durability of the tire, effectively reducing the scope of the adjustment parameters.

Aiming at the optimization scheme of the 11.00R20 tire, the tire trial production and durability test were carried out. The results show that the scheme can significantly improve the fatigue life of the tire, and the reliability of the method was further verified.

The strain energy density gradient and sensitivity analysis in the destruction of the application of radial tire fatigue can not only reduce the number of experiments during product development and shorten the product development cycle but also effectively improve the durability of the tire and further improve the application value of TBR tire fatigue damage theory and promotion of fatigue life.

Nomenclature

<i>FE</i> :	Finite element
<i>FEA</i> :	Finite element analysis
<i>SED</i> :	Strain energy density
<i>SEDG</i> :	Strain energy density gradient
<i>S-N</i> :	Stress and fatigue life
<i>TBR</i> :	Truck Bus Radial
<i>VCCT</i> :	Virtual crack closure technique.

Data Availability

All the data generated or analyzed during this study are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (51405201). The authors would like to express their gratitude to Mr. Wan Zhijun from YFKSS for his invaluable help in compiling the MATLAB program. Mr. Li Zhao from Aeolus Tyre Co. Ltd. also provided lots of help in tire contour design and the authors remain grateful.

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