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Study of over-examination on tire induced by pressure correction process in flywheel tests

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Abstract

In this paper, the strain energy density (SED) is used to study the over-examination to tire in flywheel test induced by pressure correction process. Flywheel test is the main method for evaluating tire durability, which cannot be measured on flat ground due to the variable road conditions. “Pressure Correction” is a necessary step in flywheel tests, but this process can lead to an over-examination of tire durability, which means the tire durability will be underestimated. However, it is impossible to obtain the tire durability from ideal flat ground test, so this paper utilizes the finite element method (FEM) to simulate the tire rolling condition on flat ground and differently sized flywheels, and the SED is used to evaluate the over-examination of tire durability in flywheel test. According to the results, a flywheel with too small diameter has a large amount of over-examination, and the amount caused by a large flywheel is acceptable. This methodology can be a guideline to assess the over-examination on different sized flywheel tests relative to the flat ground, and for the certain tire in this study, flywheels with 3–5 times the tire diameter appear to have an acceptable over-examination.

Keywords

Tire life prediction, flywheel test, pressure correction process, strain energy density, finite element method

Introduction

The tire is a significant component in cars and aircrafts, it plays a critical role in the safety of passengers, so its durability has received a lot of research attention. In order to evaluate tire durability, the flywheel test was invented, and has become the main way to simulate tire’s failure,[1–3] avoiding the inconvenience of a real field test on the flat ground. However, due to the curvature of the flywheel, the data obtained by flywheel tire test must have differences compared with the real using stage on flat ground. For example, when the inflation pressure is the same, the tire will deform more on the flywheel than on the flat ground under the same vertical load. After noticing this, engineers came up with a method, which could equalize the tire deformation in these two situations by increasing the inflation pressure of the tire, and this methodology is called “Pressure Correction,” which is even written into standards for tire test.[4] Nevertheless, the disadvantage of this method is that, it will increase the stress on the rubber components, this makes the flywheel test a kind of overload test because the load conditions would be more severe than those in actual use, and it would make the test of tire durability more conservative, sometimes excessively conservative and will lead to waste of resources.

As what mentioned before, tire durability cannot be evaluated on the flat ground, and all the durability tests for tires are carried out on flywheels.[5] So it is impossible to study the amount of over-examination of tire durability on the flywheel relative to the flat ground by comparing the real

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test data directly. The FEM is widely utilized to minimize the cost and the test time in tire safety assessment[6–8] and tire structure improvement,[9–11] and previous studies used FEM to predict tire fatigue life as well. For example, Yan et al.[9] analyzed tire life by extracting the strain and stress status in FEM. On the other hand, the SED is proved to be an important parameter in assessing tire durability.[12,13] Liang et al.[14] used the SED gradient to determine the location of rubber damage in tires, and proofed that the area where the maximum SED appears in FEM results is probably the damage area in the tests; Kim et al.[15] and Wang, et al.[2] found that the tire durability is closely related to the fatigue life of rubber sample, they firstly obtained the quantitative relationship between the SED and the rubber fatigue life through the rubber component test, and then estimated the tire durability through the SED from the FEM results, eventually they found that this prediction method was accurate to a certain extent. In spite of this, it could be seen that the previous research has largely overlooked the over-examination in the test of tire durability in flywheel test caused by the Pressure Correction.

In this paper, the strain energy density (SED) is used to study the over-examination of tires in flywheel test induced by pressure correction process. A type of aircraft tire model, with a diameter of 624 mm, is established and analyzed by FEM, the rolling state of the tire both on a flat ground and flywheels in different sizes is simulated; different inflation pressures are applied to simulate the “Pressure Correction” step, which is aimed at balancing the tire deformation on the flywheel and the flat ground. In the next step, the SED of the rubber component will be extracted from the FEM results, and based on it, a method to evaluate the amount of over-examination of tire durability in flywheel test compared with flat ground test is given. This method can not only be used to estimate the amount of over-examination of tire durability caused by the Pressure Correction, but also can be a guideline to help researchers to determine the suitable size of the flywheel on the basis of tire diameter, so that the wasting of resources could be reduced.

Finite element model

Modeling of tires

The tire is a kind of extremely complicated composite structure, the main problem needed to be paid attention to while modeling is the rubber-cord layer structure, which consists of rubber components, and several layers of cords embedded in the rubber. The cord can only be stretched in one direction, which is the portrait direction; while the rubber layer can deform in every direction, which means the tuber-cord layer is anisotropic.

In general, in the modeling process, the rubber materials are considered continuous, isotropic, and homogeneous hyper-elastic materials, with a highly nonlinear mechanical behavior during deformation. Scientists and engineers have raised several equations based on strain energy functions, in which the function raised by Yeoh[16] is widely used in the modeling of tires. And the form of the function is as follows

$$\mathrm{W} = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \tag{1}$$

where C_{ij} is the material constant, I_1 is the first Green deformation tensor, and its expression is

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{2}$$

where λ_1, λ_2, and λ_3 are the three principal extension ratios.

On the other hand, the cords are usually presented by the rebar model,[17] which will greatly simplify the tire model,[18] the model includes several layers of rebar elements embedded in the rubber model, and deform together with the rubber. Each layer of the rebar elements can only show elasticity in one direction, like reinforcing rebar in the cement.

In order to obtain the material parameters needed for modeling, uniaxial tensile tests of rubber and cord components were carried out, respectively. The rubber tests include the uniaxial tensile tests of each kind of rubber compound composing the tire structure, from which we got the rubber uniaxial tensile curves, and the Yeoh coefficients C_{10}, C_{20}, C_{30}, were obtained by fitting the curves. A cord is elastic in its length direction, so we obtained its elastic modulus through uniaxial tensile tests, and calculated Poisson’s ratio by comparing the diameter change before and after it is stretched.

Mesh and loading conditions

In the commercial FEM software ABAQUS, a 3D revolution solid of the tire rubber is established with several layers of rebar elements embedded in it. The rubber component is simulated by 3D hexahedral elements, and the reinforcing cord components are simulated by the rebar surface elements, the rubber part and the rebar parts are meshed using an 8-node hybrid element (C3D8RH) and 4-node quadrilateral surface element (SFM3D4), respectively. The tire section and the size of the mesh are shown in Figure

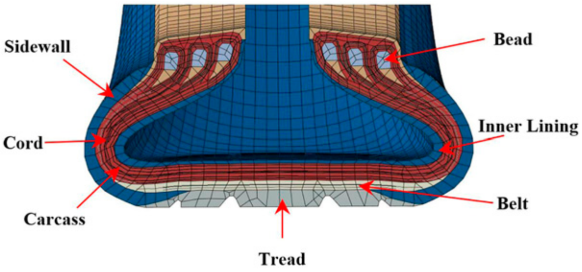

Figure 1. Schematic diagram of the tire section after being meshed.

1, which totally consist of 165,697 elements. In ABAQUS, the constitutive model of rubber is set as Yeoh hyper-elastic, and the material parameters C_{10}, C_{20}, C_{30}, are obtained from uniaxial tensile tests of each kind of rubber compound; the cord can only be stretched in one direction as it is embedded in the tire, and the rebar elements can only show elasticity in one direction, so the Young's modulus and Poisson's ratio from cord tensile test are given to rebar elements. The flat ground and the flywheels in different diameters are all modeled by rigid bodies here, and the interaction between the surface of the tire and the rigid bodies is considered as hard contact in the normal direction and Coulomb friction in the tangential direction.

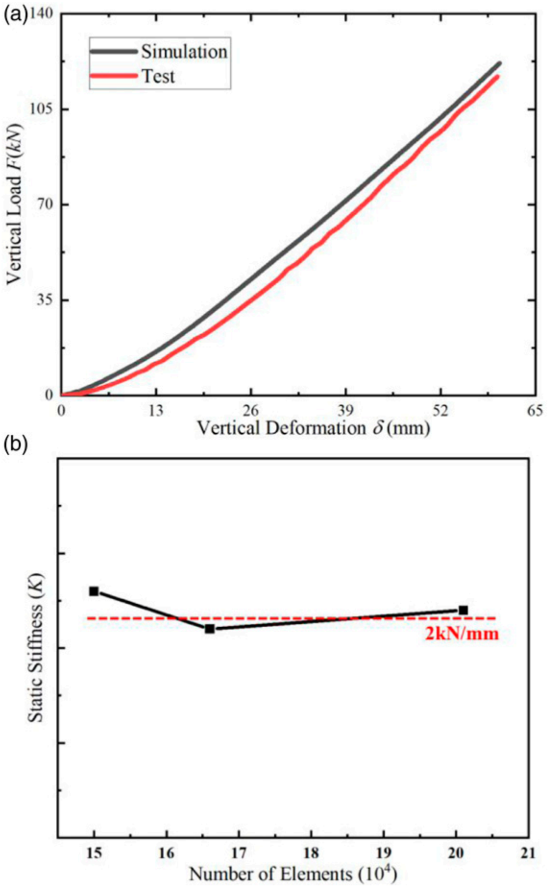

Figure 2. (a) Static stiffness curve of the real test and simulation; (b) mesh convergence study.

The static stiffness curve of the real test and simulation is compared in Figure 2(a), the two curves are very close to each other, indicating that the model has its equivalence. The convergence studies are performed by changing the number of elements used in the model, and compared the variation of tire static stiffness K, which is defined as the ratio of F and δ. From Figure 2(b), we could find that the tire static stiffness converges well when the elements number is in the range of 150,000–200,000, so the availability of the model could be verified.

For the loading conditions, there are 3 processes in this study:

1. Inflation and pressure correction. Apply uniform pressure on the inner surface of the tire to simulate the inflation process. For the Pressure Correction, different inflation pressure is applied to make up for the error of the tire vertical deformation caused by the flywheels' curvature. The relationship between the needed inflation pressure and the diameter of flywheels is gained from simulations and shown in Figure 3.
2. Static load application. The vertical load to the tire is exerted by the flat ground or the flywheels. Being adjusted by the Pressure Correction process, the deformation of the tire equals with each other in these simulations.
3. Steady rolling procedure. The rolling of the tire is driven by the flat ground and the flywheels as well, and the translational velocity of the flat ground or the linear velocity of the flywheels is the same magnitude of v, as shown in Figure 4.

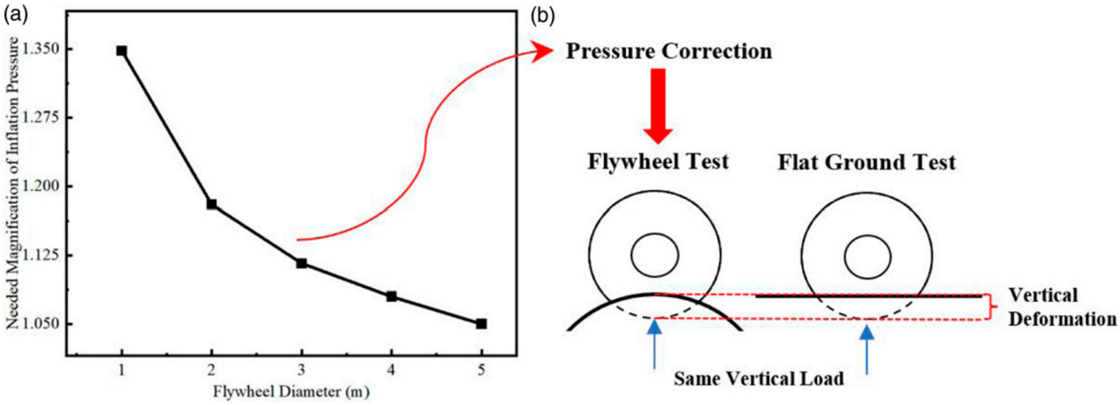

Figure 3. (a) Relationship between the Pressure Correction process and the diameter of flywheels; (b) schematic diagram of the Pressure Correction process.

Results and discussions

To date, numerous studies have investigated the criteria for the prediction of rubber fatigue life,[19–21] along the research, SED is usually used as a criterion.[22–24] At the same time, the way of evaluating the fatigue life of the rubber product, such as tires, based on the SED of rubber components, is considered reasonable,[15,25] so, we choose the same way to evaluate the tire durability in our study. As previously mentioned, it is impossible to test tire durability on the flat ground, and because of the Pressure Correction Process, the flywheel test is essentially overload tests, the result has an amount of over-examination. Thus, the objective of this research is to study the amount of over-examination on different sized flywheel test compared with the flat ground condition, and the amount of over-examination can be indirectly characterized by the relationship between SED and rubber fatigue life. Therefore, in the following analysis, the SED of some certain rubber components in the tires will be extracted, and compared with each other, considering the effect of the Pressure Correction process. Then the tire fatigue life will be evaluated based on these rubber components, and eventually, the amount of over-examination of tire durability on different sized flywheel test compared with the flat ground condition will be studied.

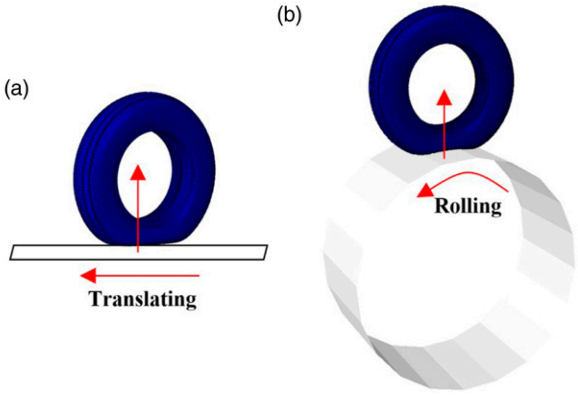

Figure 4. Steady rolling procedure for (a) simulation on a flat ground; (b) simulation on a flywheels.

Results from simulation of flat ground and simulations of flywheels

To have a comparison of the simulation on flat ground and simulation on flywheels, the result of steady rolling procedure in the simulation of flat ground is presented here firstly. Figure 5 shows the distribution of SED on rubber materials of the tire in the middle cross-section, it could be observed that the maximum SED concentrated in the zone near the tire shoulders. The zone near the shoulders is widely regarded as a vulnerable area of frequent destruction in tires because more deformation energy will accumulate in this region.[8]

Flywheels of different sizes are established, with the diameter of 5 m, 4 m, 3 m, 2 m, and 1 m, the Pressure Correction process and the steady rolling procedure in Figures 3 and 4 are applied in the flywheel simulations as well. Because of the decrease in flywheel diameter, the needed inflation pressure has to increase (Figure 3), so the SED near the tire shoulder will become larger, which could be seen from Figure 6.

Influence of Pressure Correction on the amount of over-examination

Firstly, the area where the maximum SED appears is near the shoulder, on the carcass rubber component. As shown in Figure 7(a), an array of elements on the carcass rubber named T_1–T_5 have been selected to extract the SED, and the variation of SED with Pressure Correction is analyzed in Figure 7(b). The corresponding inflation pressure in the

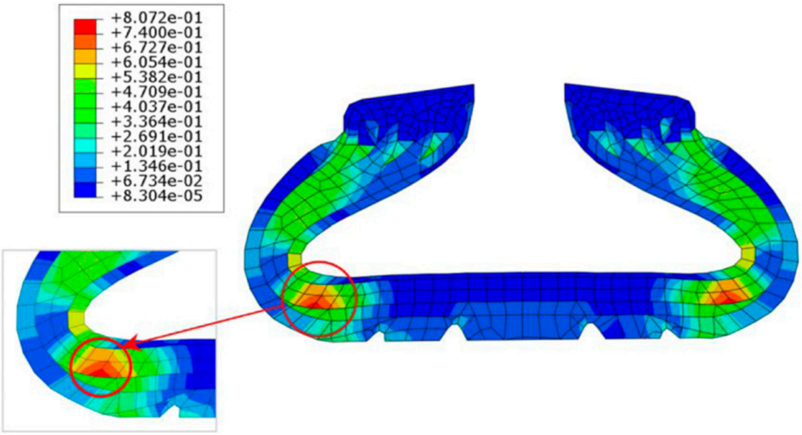

Figure 5. Distribution of SED on rubber materials in plane simulation, from the middle cross-section.

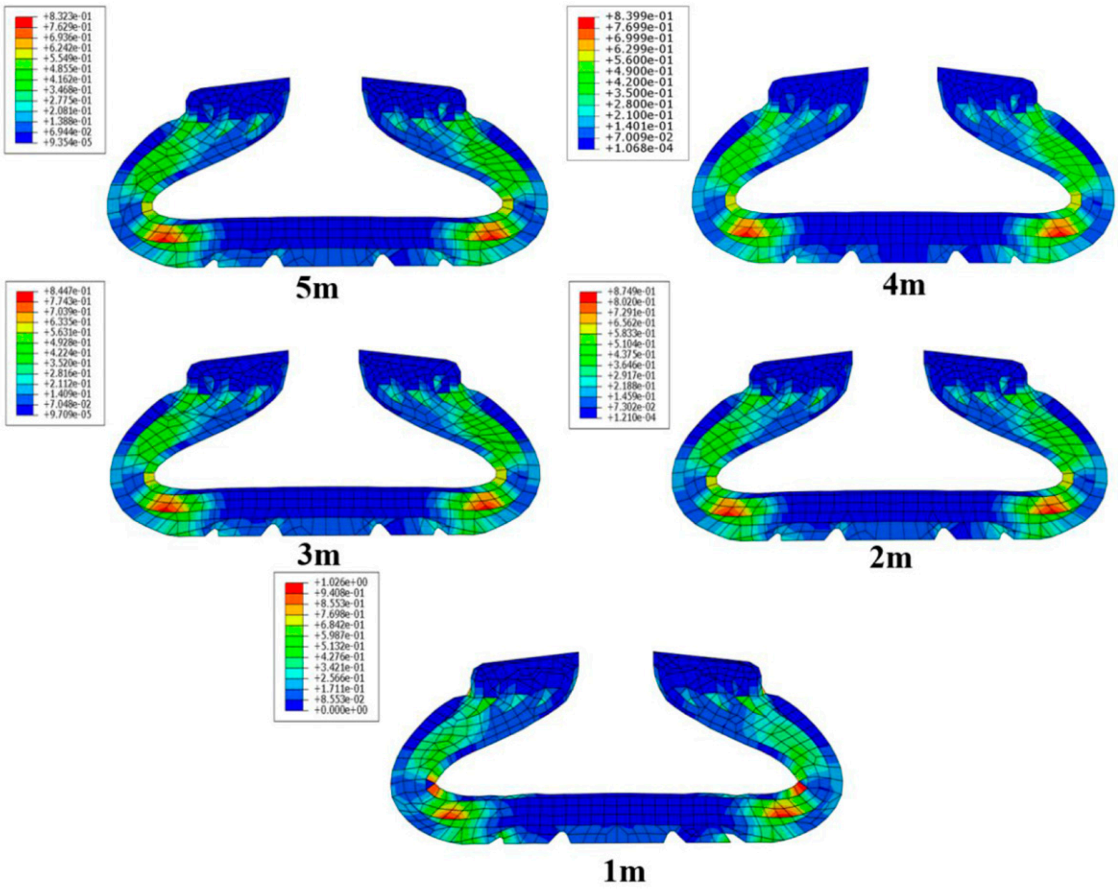

Figure 6. Distribution of SED in the middle cross-section of the tires when contacting with differently sized flywheels.

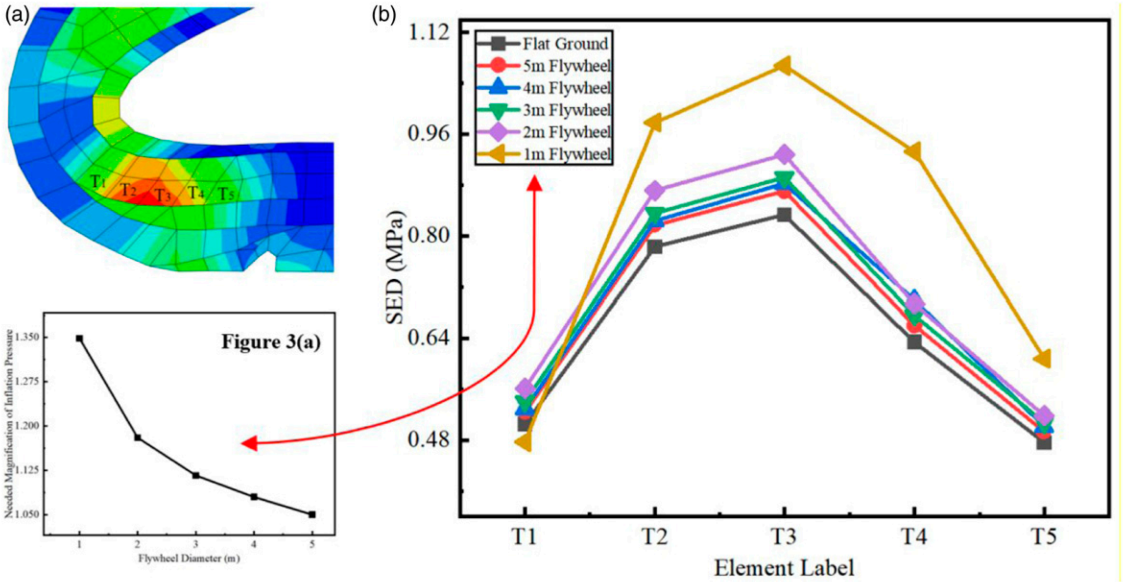

Figure 7. (a) The schematic of the vulnerable area at the carcass rubber with the element label; (b) the distribution of SED on the labeled elements and the changing trend with the varying flywheel diameter; the magnification of the maximum SED obtained from the flywheel simulations to the flat ground simulation.

Pressure Correction procedure has been shown in Figure 3(a), which is substituted into Figure 7(b). It can be found that, under the effect of Pressure Correction, when the flywheel diameter is 2 m to 4 m, the maximum SED increases slowly with the decrease of flywheel diameter; while when the flywheel diameter is smaller than 2 m, the increase of maximum SED is particularly pronounced.

In many studies, SED is regarded as a good criterion to predict the fatigue life of rubber,[19] for it is a product of stress and strain, so it would express the stress state of an element relatively neutrally. For rubber materials, the relationship between SED and fatigue life is expressed by the power-law expressed as equation (3)[25]

$$SED = K\left(N_f\right)^b \tag{3}$$

where N_f is the fatigue life, K and b are the material constants. Equation (3) could be written as equation (4) in order that the amount of over-examination of tire durability on the flywheels could be evaluated

$$W = \frac{N_{f0} - N_{f1}}{N_{f0}} = 1 - \left(\frac{SED_1}{SED_0}\right)^{\frac{1}{b}} \tag{4}$$

Here the N_{f0} and SED_0 are the tire durability and SED from the result on the flat ground, and N_{f1} and SED_1 are the tire durability and SED from the result on the flywheels, W is the amount of over-examination. The rubber materials used here in the tire are all filled with rubber, thus the magnitude of the material constants K and b in literature[22] is used here as a demonstration of the methodology, and b is -0.55.

The result calculated by equation (4) is shown in Figure 8(b). In Figure 8(b), P_0 means the inflation pressure in the flat ground simulation, and P_1 is the inflation pressure in the flywheel simulations after the Pressure Correction process, and the Pressure Correction factor P_1/P_0 is on the basis of the ratio of D/d, where d and D are the tire diameter and flywheel diameter, respectively. Figure 8(b) indicates that the magnification of the maximum SED in flywheel simulations to the flat ground simulation shows a positive correlation with the increase of the inflation pressure, which is in accordance with Figure 7(b). To be more specific, when P_1 is more than 1.3 times P_0, and D is less than 1.8 times d, the magnification SED_1/SED_0 will exceed 120%, and the amount of over-examination W is over 30%, which is remarkable. And when the correcting pressure P_1 is less than 1.1 times P_0, and D is more than 4.8 times d, the magnification of SED and the amount of over-examination W, less than 10%. In the middle part of this range, the amount of over-examination W is acceptable, which is during 10% to 20%.

It can also be concluded by combining Figure 8(a) and (b) that, for the certain aircraft tire we study here, when the flywheel diameter D/d is more than 6.4, the over-examination will come into a plateau where the value is small, at this time, the diameter of the flywheel is more than 4 m, so the flywheels larger than 4 m are unnecessary to conduct the tire test. On the other hand, when the flywheel diameter D/d is less than 3.2, specifically when D is smaller than 2 m in this paper, the amount of over-examination is beyond the acceptable range, thus, a flywheel smaller than 2 m could not be used. So, the diameter of suitable-sized flywheel in this paper should be in the range of 2 m–4 m.

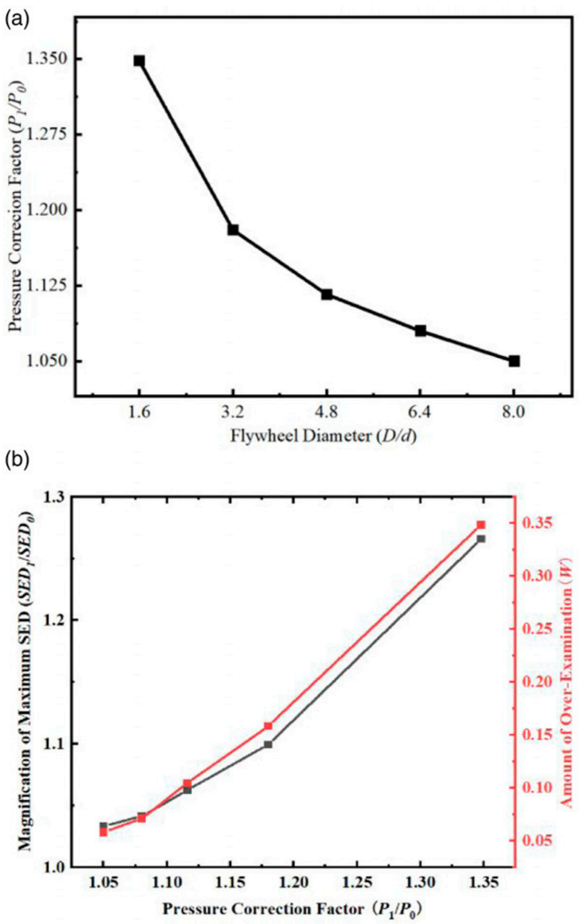

Figure 8. (a) The relationship between the flywheel diameter D/d and the pressure correction factor (P_1/P_0); (b) the changing trend of the maximum SED and the amount of over-examination for the tire as the variation of the inflation pressure.

In addition, considering that the simulation is an ideal condition and there is an error between it and the actual condition, error analysis is needed to estimate the accuracy of the amount of over-examination. The SED is used to estimate the durability of 2 types of tires in literature [2] and [15], the estimation results are compared with flywheel tests, and the errors obtained are 1.3% and 8%, respectively, with an average of 4.6%. As for the durability on the flat ground, because the real test could not be carried out, the error cannot be estimated, so the ideal flat ground condition in the FEM is still regarded as the reference for comparing the amount of over-examination. Equation (4) is used to correct the error of the amount of over-examination

Table 1. The error correction of the amount of over-examination.

	Amount of over-examination	
Flywheel/tire diameter ratio	Before corrected, (%)	After corrected, (%)
1.6	35	31.4
3.2	15.8	11.1
4.8	10.4	5.4
6.4	7	2
8	6	1

concerned in this paper, and the specific value is shown in Table 1 below:

It can be seen from Table 1 that after the error correction, when the diameter ratio is 6.4–8, the amount of over-examination is only 1%–2%, but in practice, such a large flywheel will not be used for testing, because spinning the flywheel requires too much energy. When the ratio of diameter is 3.2–4.8, the amount of over-examination is more acceptable; but when the flywheel diameter is 1.6 times the diameter of the tire, the amount of over-examination can still reach to 31.4%.

To sum up, flywheel test, as a kind of overload test, has a certain amount of over-examination compared with the flat ground condition, and because of the Pressure Correction Process, the amount of over-examination is negatively correlated with the ratio of flywheel diameter and tire diameter, that is, the smaller the flywheel, the greater the amount of over-examination, actually tire durability has a lot of reserves. This has a certain reference value for engineers to evaluate the amount of over-examination.

Conclusions

In this study, a new method to evaluate the amount of over-examination of tire durability due to the Pressure Correction process in tire flywheel tests has been suggested. The suggested methodology used a steady rolling FEM analysis on differently sized flywheels and a flat ground, respectively, then a method based on SED is used to estimate the amount of over-examination of tire durability on flywheels compared with flat ground. The conclusions are as follows:

1. Based on the tire we studied here, when it is rolling on the flat ground or the flywheels, the maximum SED occurs in the carcass rubber near the shoulders, which matches the regulation of destruction area in the general situations. Additionally, due to the effect of the Pressure Correction process, the magnitude of the maximum SED at the vulnerable area in the tire will increase as the rising of air pressure, and the aire pressure will rise with the decrease of the flywheel diameter.
2. Prediction criterion for rubber fatigue life based on SED, which has been proved to be a reasonable way, is used here to analyze the over-examination that appears in the Pressure Correction process on flywheels of different diameter. From the result, the amount of over-examination is of positive correlation with the increase of pressure correction factor.
3. The methodology mentioned in this study could be a guideline for engineers to evaluate the amount of over-examination, and for different types of tires, the evaluation has to be considered, respectively. For example, for the tire in this paper, when the flywheel diameter is less than 3 times the tire diameter, dramatic over-examination would occur, and tire durability might be remarkably underestimated. When the ratio of diameter is larger than 3 but less than 5, the amount of over-examination could be acceptable. And when the flywheel diameter is more than 5 times the tire diameter, the amount of over-examination of flywheel would not increase distinctly.

Declaration of conflicting interests

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