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Finite Element Analysis for Development of Fail-Safe Truck Radial Tires under Extreme Operating Conditions

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Abstract

Truck is one of the main on road commercial vehicle which is used for carrying the load from one place to a distant place. Every vehicle is designed for sustaining a particular amount of load at particular inflation pressure. However in realty, often the truck drivers travel long distances at extreme loading conditions e.g. very high load at very high inflation pressure, very high load at very low inflation pressure. Generally tires are not designed to sustain such extreme conditions and fails in the critical regions. However, in order to meet end customer demands, tire manufacturer need to make sure that the truck tire performs well under such extreme conditions. There are huge time and cost involved in iterating through making prototype tires and carrying out field trials.

This work provides an approach for evaluation of the truck tires through FEA approach before manufacturing actual tire. A study is carried out to analyse the effect of tire structure on tire durability at critical regions under extreme loading conditions. Suitable durability parameter is identified from the simulation that corresponds the durability of the tire. The simulation results are validated with indoor testing results and accordingly a batch of tires produced and sent to the market for field trial. Tire durability in the field trial is also found in agreement with the durability parameter in the FEA simulation.

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Introduction

Tire is the critical component of the vehicle as it is the link between the vehicle and the road. Tires are designed to perform under a standard load and standard inflation pressure. In case of truck tires it is observed that standard operating conditions are not maintained by the drivers for example in India trucks run under overloading conditions. These overloading conditions drastically reduce the life of the tires that are designed and manufactured targeting the standard operating conditions. Therefore, tire designers need to develop tires which may sustain under severe overloading conditions.

Tire is a complex composite structure made of rubber, steel wires and fibre all of which are quite different from each other in terms of properties e.g. low modulus of rubber vs high modulus of steel cords. Apart from the structural complexities, it exhibits highly non-linear behaviour while rolling on the road. Tire is under tight contact with rim and road. Whenever a certain sector of tire comes in contact with road, it is bound between rim and road. While coming in contact with road, tire deflects radially, which makes the internal structural components to flex against each other at the frequency of the tire rotation. Tire structure contains discontinuous ends of steel and fibre cords, which act as a slow poison for nearby rubber components of the structure. Due to the huge differential in modulus of rubber and steel, rubber gets damaged under repeated loading of the tire[1-4].

Bead is an important component of the tire which remains very near to the rim. There are various ends of steel cords which lie near the bead region. Most of the truck tires fail near the bead region due to reasons as mentioned above. The durability of bead region depends on the strength of structure and rubber. Therefore, tire manufacturer carries out indoor tests (Figure 1) to characterize the tire performance before actually releasing them to the market.

Figure 1: Indoor testing rig for bead durability

Prior to finalizing a design, many iterations with different designs are evaluated. Manufacturing and testing of each iteration consumes lot of time and money. In order to accelerate the design cycle, simulation technique is used where performance of the tire is measured using finite element analysis before actually manufacturing it[5]. Another advantage of simulation is that it

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provides insight to the internal failure mechanisms of the tire which is not possible otherwise using the physical tests. However, limitation of the simulation approach is that it need extensive computational resources. Carrying out the simulation of complete indoor testing procedure will take enormous computational resources[5].

In the present work, a methodology is proposed for indoor testing of the tire for overloading conditions and also a simulation approach is suggested for computation of tire durability parameter. A case study is carried out which shows the durability criteria from the simulation is closely correlating with the indoor testing and field trial of the tires.

Indoor Testing

Figure 1 shows a typical indoor testing setup, where the tire is inflated to the designated inflation pressure and pressed against the rigid drum with designated load. The tire is continuously run against the drum at a prescribed speed in this condition till the failure of the tire. Time taken for failure of the tire represents the tire durability in the indoor test conditions.

Simulation procedure

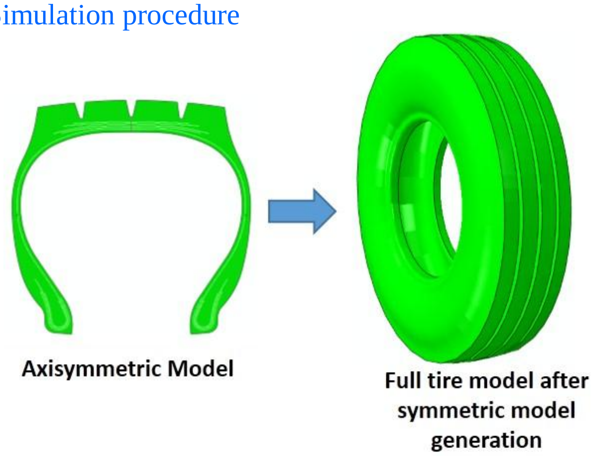


Figure 2: Tire Model

Figure 2 shows the typical cross section view of a tire as well as full 3D model of the tire. Hypermesh is used for meshing the axi-symmetric tire and Abaqus is used for finite element simulation. The rubber components are modelled with solid elements. The fibre-reinforced components are modelled with shell elements. The rim and road is modelled as rigid part. First step of the analysis is the inflation of the tire with internal pressure. Axi-symmetric model is used for this analysis. Table 1 shows the element types used for axi-symmetric analysis. Further the axisymmetric model is revolved about the central axis of the tire and stress field obtained from inflation analysis is applied as the initial state for full tire[5-7]. Table 2 shows the element types for 3D analysis of the tire Table 3 shows the material models for various structural components of the tire. Coefficient of these models are evaluated after carrying out tests on the samples in the laboratory.

Table 1: Element types used in inflation analysis

Element shape	Triangular	Rectangular	Linear
Element Type	CGAX3H, CGAX3	CGAX4H, CGAX4	SFMGAX1

Table 2: Element Types used in loading analysis

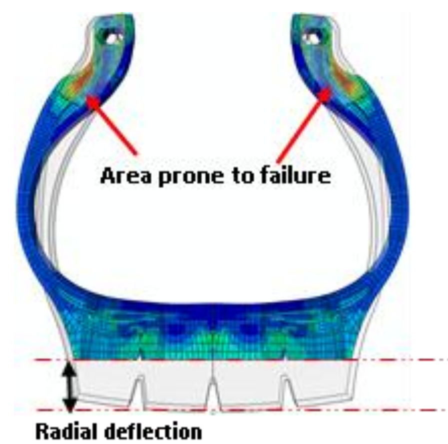
Element shape	8 Noded Brick	6 Noded Brick	Surface
Element Type	C3D8H	C3D6H	SFM3D4R

Table 3: Material models used in different components

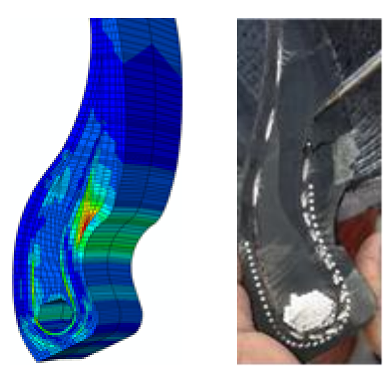
Component	Rubber	Steel cords	Fiber	Bead
Model Type	Hyperelastic, Yeoh	Hyperelastic, Marlow	Hyperelastic, Marlow	Elastic

On the basis of literature and experience, the best correlative parameter for bead durability for truck tire are strain energy, shear stresses and strains near bead region[3]. On the basis of these a durability parameter is formulated which is function of strain energy, shear stress and strain. Higher value of durability parameter is preferred for better performance of the tire.

Bead region failure in the tire is observed from the tires in the field trial. Further simulation is carried out and durability parameter is evaluated. Figure 3 shows the contour plot of durability parameter on the tire cross-section and zoomed view in the bead region. In order to show the failure, red colour represent low value of durability parameter. Figure 3c shows the actual failed tire in the bead region. It is observed that the tire durability parameter is low at the region, where it actually failed. It shows the durability parameter represent the tire durability characteristics closely.



(a)



(b) (c)

Figure 3: (a) Contour plot of durability parameter along the cross-section, showing tire deflection and failure region, (b) zoom view near the bead in simulation and (c) failure in the actual tire near bead

Case study

Two different of designs of truck tire are shortlisted for durability evaluation. Simulations are carried out for these two designs. Tires are manufactured based on both designs and subjected to indoor test as well as field trial. This case study showcases the finding of simulation, indoor test and field trial in terms of tire durability.

Simulation Study

Simulation technique was used to evaluate the designs before actually making the tyres. Ply line curvature was the basic difference between the two designs. These two designs namely *D1* and *D2* were evaluated under three different operating conditions namely *C1*, *C2* and *C3*. Details of these 3 operating conditions and regular operating condition are shown in the Table 4. These 3 cases represents low inflation – high loading, high inflation – high loading and high inflation – low loading respectively. These 3 scenario are selected based on the field report on practices followed by the truck drivers with respect to the inflation pressure and loading of the truck.

Table 4: Operating conditions (inflation and load)

Condition	Inflation Pressure (psi)	Load (Kg)
Regular	120	3000
C1	120	4500
C2	150	4500
C3	150	3000

1. Low inflation – high loading (C1)

This scenario is important where truck drivers put high load on their truck, without changing the inflation pressure. Figure 4 shows the performance of designs D1 and D2 in this case. It is observed that design D2 is superior in this condition.

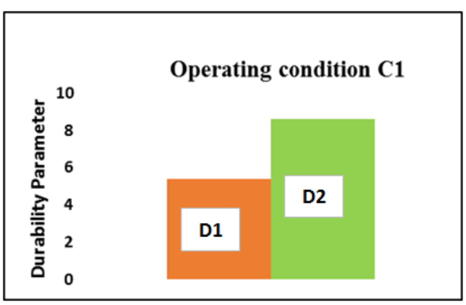


Figure 4: Durability parameter at bodyply end at regular inflation, high loading (C1)

2. High inflation – high loading (C2)

This scenario is for the drivers who inflates the tire more for driving with high load. So they run their vehicle at high inflation pressure and high loading conditions. Figure 5 shows relative durability parameter for both design in this scenario and it is observed that design D2 is superior in this case also.

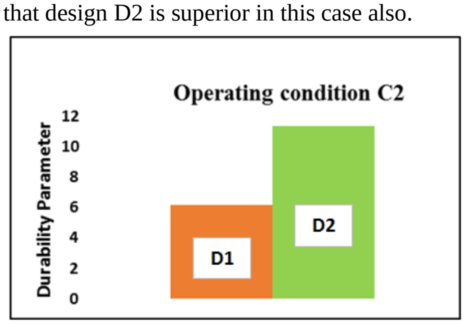


Figure 5: Durability parameter at bodyply end at high inflation, high loading (C2)

3. High inflation – low loading (C3)

Drivers put high inflation whenever they have to carry high load from one place to another. However, after unloading the vehicle they generally don't deflate the tires. So they run the vehicle at high inflation but at regular load. Figure 6 shows the durability parameters for both of the designs in this scenario. It is observed that the design D2 performs better.

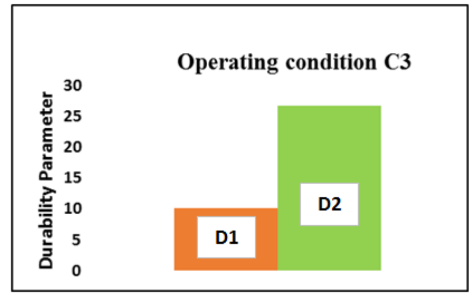


Figure 6: Durability parameter at bodyply end at high inflation, regular loading (C3)

A comparison of durability of design D2 (better out of the two) for the scenario C1 and C2 shows that scenario C2 results in higher durability of the tire.

Indoor Testing

Indoor durability test results are given in terms of durability rating from 1 to 5, with 5 as best and 1 as worst. This rating is derived from the number of hours run by the tire before actual failure. Method for computation of the rating is confidential and cannot be shared. Tires from design D1 and D2 are subjected to indoor testing after manufacturing them at the CEAT plant in Halol, Gujarat. Table 5 shows the comparison of indoor test findings. This observation is in-line with the findings of simulation in terms of tire durability.

Table 5: Indoor test ratings of tires

Tire Design	Indoor Testing
D1	3
D2	4

Field Trial

Tires made from both of the designs are evaluated in terms of claims in 3 month period in the market. Further based on past experiences the claim report is converted into rating of tire in which 1 is the worst and 5 is the best. Method for computation of the rating is confidential and cannot be shared. Table 6 shows the comparison of simulation, indoor testing and field rating for both sets of the tires. It is observed that tire made of design D2 resulted in lower claims i.e. higher durability. This observation is in-line with the findings from the indoor tests and simulation.

Table 6: Comparison of tire performance in simulation, indoor testing and field trial

Tire	Simulation			Indoor	Field
Design	C1	C2	C3	Testing	Trial
D1	5	6	10	3	2
D2	9	11	27	4	4

Conclusions

1. Design of internal structure of tire has great importance from tire durability perspective.

2. Simulation technique can be used for predicting the life of tire with suitable durability parameters.
3. FE Analysis which takes care of tire design and material complexities when coupled with suitable operating conditions, can be used for analysing and developing the tires that will perform well in overload conditions.

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