Failure analysis of strut top rubber bush & sensitivity study using multiple material models

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Abstract:

Stress analysis of rubber components is often demanding on account of difficulties posed by complex behavior of rubber. When it comes to fatigue predictions of rubber components, this complexity increases multifold. Further, in time bound development projects, it becomes very difficult to dedicate sufficient time to tests and gather data required to characterize rubber accurately. In such cases, more practical approach is to make design improvements through simulations based on approximate rubber models followed by validation through physical tests.

Correct choice of hyper-elastic material model that is to be derived from limited test data is a key to success of this approach. It is seen that incorrect choice of material model may lead to erroneous results and misguide design changes. When it is expected to use material model to predict multiaxial stress state under given loading, rubber characterization in various pure stress states is essential to fit material models correctly. In absence of such data, in this approach, multiple material models are used to study the trends and to assure that choice of material model is not affecting trends.

In this paper, this approach is applied successfully to resolve test failure issues through design improvements guided by simulations. CAE and test results are discussed in detail.
Introduction

The strut mount is located on the top of the strut assembly and is used to provide a pivot point and mounting location for the strut. The strut mount is used on cars equipped with Mac Pherson type struts, and are typically found on smaller compact cars. The strut mount is typically made of rubber and has a strut bearing in the center that allows the strut to turn right to left with the steering. It is designed to prevent sudden excitation of the car body through road input, bumps, obstacles, pot holes etc. To absorb impacts on strut, bush needs to be softer, at the same time it should be durable against repetitive loads. Bush helps reducing tyre induced noise as well. Problems such as knocking noise while going over bumps and hard steering while turning the wheel are attributed to strut mount failure.

CAE simulations are often used to evaluate the different designs using nonlinear analysis techniques. Typically, analysis of rubber components is complex and time consuming process. This paper describes failure analysis of strut top bush during operation with limited material test data, with the aid of CAE tools.

Complexity involved in analysis of Rubber material

Rubber like material exhibit a highly nonlinear behavior characterized by Hyperelastic deformability and incompressibility. It’s a material which can withstand very large strain from 100% to 1000% without any permanent deformation. The typical stress-strain curve in tension is noticeably nonlinear so that Hook’s law can not be used and it is not possible to assign a definite value to the young’s modulus except in the region of small strains.

Rubber exhibit complicated mechanical behavior as it can undergo large deformations. Other effects like viscoelasticity and Mullins effect are also important. Its stress-strain relation is dependent on nature of loading.

Figure 1 (a) shows the results of the simple tension test. The stress-strain relations of the rubber changed drastically during the first several cycles, and stabilized after 3 to 4 cycles, which is know as Mullin’s effect. Figure1(b) shows the typical stress and strain curves of the natural rubber for simple tension, Equibiaxial tension and planner test loading to maximum strain of 100 percent (‘S’ Shape behavior).

Figure 1 (c) shows the elastic components change with temperature and strain rate. Figure1 (d) shows stress relaxation effect of rubber which is also known as viscoelastic decay which means if the same elastomer is

Figure1 (a): Mullins effect     Figure1 (b): ‘S’shape behavior
stretched to particular strain and held, the stress will decrease over time. These characteristics present complications to the modeling of rubber compared to other traditional engineering materials such as steel.

![Figure 1 (c): Temperature sensitivity](image1.png)  ![Figure 1 (d): Stress relaxation effect](image2.png)

**Material modeling basics and experimental tests**

There are two main approaches in studying rubber materials such as continuum mechanics and phenomenological. Both approaches generally derive the strain energy density as a function of strain or deformation. Derivative of strain energy density with respect to particular strain component determines the stress in the component. Thereafter established stress-strain relation can be used for finite element analysis.

Among the various material models used for rubber are Mooney Rivlin, Neo Hooken, Marlow model which comes under phenomenological material models. And also Ogden, Yeoh, Aruda Boyce and Ven-der-waals which belongs to continuum mechanics material models. In order to use these material models for CAE simulation, in both approaches it is necessary to have sufficient test data.

Objective of the testing is to achieve “pure” states of strain such that the stress strain curve represents the elastomer behavior only in desired state. Intension is to model the behavior of the material in the working range of strain and stress. Sufficient experimental data should be available to fit mathematical material models. For a homogeneous material, homogeneous deformation modes suffice to characterize the material constants. Figure 2 and 3 give all such deformation modes and its equivalent testing modes.
Poor material model will often lead to erroneous results. Ideally test data from all these test type is required to characterize the hyperelastic material behavior.

Most of these models are referred to as hyperelastic material models. It’s beyond the scope of this paper to discuss the details of particular hyperelastic material models. In general, stress and strain data sets developed by stretching the elastomer in several modes of deformation are required and fitted to sufficiently define the parameter of the material models.

For rubbers, the basic strain states are
- Simple tension strain state,
- Pure shear strain state
- Simple compression strain state and Equi-biaxial strain state.
For experimental reasons, compression is replaced by equal biaxial extension.

All the tests required specific test setup, specimen of specific shape to gather the stress-strain data. When it is difficult to dedicate sufficient time to test and generate required data to characterize rubber accurately. In such cases, more practical approach is to make design improvements through simulation based on approximate rubber model making use of available test data only.

**Finite element analysis of Strut top bush failure**

Figure 4 and 5 shows, strut top bush assembly of front suspension. Strut top bush typically consists of rubber bush bonded with inner and outer steel sleeve. The whole preloaded assembly of strut top bush and shock absorber is mounted on to the vehicle as part of front suspension assembly thus absorbing the vertical forces coming during service load conditions.
Life of the strut top rubber bush mainly depends on the bonding with the metallic sleeves and life of rubber bush itself. Rubber bush life is dependent on the stresses due to vertical and radial load coming onto the rubber bush while going over the bumps, potholes. During torture track testing of the vehicle the bushes were failed at 50 percent of the target life. Figure 6 shows one such failed sample of strut top bush during the torture track testing of the vehicle. The cracks has initiated after certain number of torture track cycles.

In understanding of possible causes of premature failure, CAE simulations provide great help. CAE simulations can be used for assessing trends, in different design proposals of the rubber bush using limited material test data.

The torture track failure is converted into equivalent block cycle test schedule using RLD data. The loads measured are converted into deflections based on component stiffness. A target acceptable stress level in the rubber bush is set based on the number of cycles completed till failure and the torture track target cycles. The maximum stress targets are derived from the available S-N curve. The life improvement by 2 to 4 times by reduction in stresses by 25% -35 % is evident from S-N data .So the stress reduction of 30-35 % is taken as target for the proposed design over baseline design.
Discretization of the steel sleeve and rubber bush is done using hexahedral elements. C3D6 and C3D6H elements are used for steel sleeve and rubber bush respectively. Tied contact is defined between steel sleeve and rubber bush. Sleeve outer is constraint in all degrees of freedom at bolting locations. Preload and external load in terms of deflection is applied at the center of inner steel sleeve.

Figure 7: FE model and boundary conditions of strut top bush.

Figure 8 shows details about the existing and proposed design of strut top bush. The proposed design mentioned below is evolved through iterations. In this paper only existing and final proposal detail results are described using different material models. The rubber profile plays a major role in the durability of rubber. In order to capture proper fillets the mesh size is kept fine.

Figure 8: FE model and boundary conditions of strut top bush.
Test data and material models used for simulation.

While working with stringent time constraints and in absence of complete set of test data, required in characterizing rubber accurately, it has been decided to use only measured uni-axial tension data for the simulation. Different material models which best fitted with the measured data are used in the simulations. Figure 9 shows comparison of various material models stress-strain data against measured uniaxial tension stress-strain data calculated for Abaqus best fitted curve technique. Material model best fitted with measures data in Uniaxial. Response in other deformation modes (like bi-axial, Planner) are derived using same model. Both phenomenological and micromechanics based material models can be evaluated using Abaqus best fitted curve technique.

In this paper analysis results using Neo Hooken, Marlow, Vender-waals, Yeoh and Aruda Boyce material models are shared.

![Material models comparison](image)

Figure 9 Comparison of different material model against test data.

Figure 10 shows the sequence of proposed design evolution. The proposed design of strut top bush is achieved through many CAE iterations. Describing all CAE iterations results are not in scope of this paper.
The high stress location matched with the location of test and field failures. Target reduction in the maximum stresses is achieved through various design iterations. Hence proposed design is further analyzed with different material models to assure same trends in the stresses response. This is done to mitigate possible chances of error on account of inadequate material model being used for evaluation in absence of complete set of test data.

**Analysis results:**

The comparison of stress results using Neo Hooken, Marlow, Yeoh, Aruda Boyce material models are shown Figure 11.

The high stress location matches with the failure location during test for all material models. There is ~30-35% reduction in the maximum stress in the proposed design compare to existing design for various the material models, though value of actual stresses are quite different as expected.

In final proposed design ~30-35% reduction in the maximum stress as compare to existing design is achieved. In this design significant improvement is expected. Hence it is decided to clear it for physical testing. Refer Table1 for physical test summery of existing and proposed design.
Figure 11: von-Mises stress comparison of Strut top rubber bush design using various material models.

Table 1: Physical test summery

<table>
<thead>
<tr>
<th>Test</th>
<th>Existing design</th>
<th>% of target Cycles completed</th>
<th>Proposed design</th>
<th>% of target Cycles completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>TML Rig (Target 100 %)</td>
<td>Sample 1</td>
<td>46 (F)</td>
<td>Sample 1</td>
<td>143 (NF)</td>
</tr>
<tr>
<td></td>
<td>Sample 2</td>
<td>80 (F)</td>
<td>Sample 2</td>
<td>160 (NF)</td>
</tr>
<tr>
<td>4 Poster (Target 100 %)</td>
<td>Sample 1</td>
<td>15 (F)</td>
<td>Sample 1</td>
<td>37 (F) bonding failure</td>
</tr>
<tr>
<td></td>
<td>Sample 2</td>
<td></td>
<td>Sample 2</td>
<td>100 (NF)</td>
</tr>
</tbody>
</table>

Note: F & NF represents failed and Not failed status

Conclusion

While working with limited test data, it has been decided to work with multiple material models to assess design improvements with minimum risks. This hybrid test-CAE approach was proved to be successful in making design improvements in very short period of time with limited test support.

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