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Responses from laminated rubber bearing under compression and rotation via FE analysis

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ABSTRACT: Bridges experience translational movements and rotations caused by creep and shrinkage, thermal effects, traffic loading, initial construction tolerances, and other sources. Bridge bearings are designed and built to accommodate these movements and rotations while supporting required gravity loads and providing the necessary restraint to the structure. In this paper, the responses of laminated rubber bearings subjected compression and rotation were simulated using a nonlinear finite element analysis technique. Rubber has been modeled as hyperelastic nearly incompressible material with the Yeoh hyperelasticity model. The results revealed the necessity of giving special attention to reduce stress concentration at the edges via an appropriate design modification, if possible at all to improve the performance not only under rotational loading but also to make it durable against fatigue.

1 INTRODUCTION

Rubber bearings have been used in bridges since the late 1950s, and have grown in popularity and they are now the most common type of bridge bearing all over the world. These bridge bearings undergo complex deformation mode such as rotation at the time of conforming to movements such as creep, thermal expansion and vibration resulting from live load traffic. This is typically the result of the end rotations of the girder as it bends about its major axis. Such a rotational degree of freedom operates in addition to axial deformation. In the base-isolation bearings, rotational deformations occur during strong earthquakes (Kelly 1997). However, the responses of rubber bearings to imposed rotations have been found to be unsatisfactory compared to their responses in compression, shear and other deformational modes. Whenever large rotation loads occur, designers tend to use pot, disk, or spherical bearings instead, as the limited rotation capacity of a rubber bearing may practically prove more of a limit than the load capacity. However those bearing have their own issues to be addressed.

A larger bearing with a higher shape factor (ratio of loaded area to force free area) would carry the axial load better, but it would reduce the bearing's ability for rotations. It is worth noting that such design involves the use of a combination of compressive and rotational loadings and this combination presents challenges. The axial load is a force, yet the rotation is a displacement. Designing for both simultaneously requires that the bearing be stiff in compression yet flexible in rotation. That may be difficult, because the features (size, shape factor) that make it stiff in compression also tend to make it stiff in rotation.

One principal cause of such problems is the traditional approach of steel plate arrangements. Continuing steel shims up to the side cover increases the axial stiffness and strength, but it reduces the ability of the bearing to rotate. In such arrangements, large stresses due to rotation tend to develop near the edges of bearings and the overall capacity is also affected. To increase the rotational ability, one solution can be to increase the height of the bearings. However increasing the height of the bearings can increase the manufacturing cost. Reducing the steel shims inside the bearing can increase the rotational ability, however stresses at the edges of the internal plate may increases and thus make it vulnerable to fatigue failure. An optimum combination of steel shim size inside the bearing needed to be found out for required rotational ability and durability against fatigue.

Laminated rubber bearings have mainly been investigated by experiments to understand their mechanical behaviors and thereby confirming the performance. However, in such experimental investigations, it is difficult to ascertain the stress fields and deformation patterns throughout the rubber mass. FEM remains as the other but only a viable way of predicting local deformations and stresses while still element instability and difficulties with convergence of the iterative calculations remain as daunting challenges in such computational approach.

In this paper, the responses of laminated rubber bearings with different internal steel plate arrangements subjected compression and rotation were simulated using a nonlinear finite element analysis technique. Rubber has been modeled as hyper-elastic nearly incompressible material with the Yeoh hyper-elasticity model.

2 BEARING SPECIMENS

Incorporation of steel at alternate layers gives combination of horizontal flexibility and vertical stiffness in rubber bearings. Traditionally, in designing such bearings, the length and width of steel and rubber layers are kept equal and the grade of rubber is not varied within a single bearing. However to improve the rotational capability of the bearings, here the intermediate steel plates have been shortened while softer (G=0.8MPa) natural rubber have been placed on the outer parts and harder (G=1.2MPa) natural rubber in the inner parts.

In this research, three bearing specimens were used (referred to here as Type-1, Type-2, Type-3) with different steel plate arrangements inside to investigate the response, both under compressive and rotational loading together. It is to be mentioned that the total bearing size was kept the same with square dimension having 270mmx270mm and total height of 66.5mm. The geometry and material specimens for each type have been given in Table.1 with schematic diagram in Figure.1

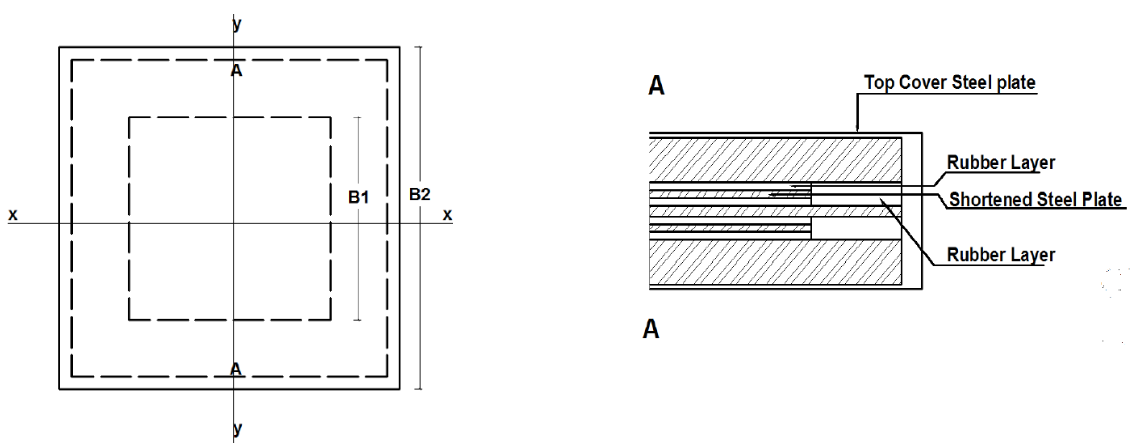

Figure 1. Bearing Specimen

Table 1. Dimension of the internal steel plates (mm)

	Type-1	Type-2	Type-3	Conventional
B1	100	130	160	250
B2	250	250	250	250

3 FINITE ELEMENT ANALYSIS (FEA)

The bearings considered in this study being square in shape the response are same and symmetrical in all directions. For this reason half of the original size of the bearing was modeled for numerical analysis. Abaqus 6.11 finite element software was used for this purpose and static nonlinear analysis was performed considering the finite strain theory.

3.1 *FE Modeling and Loading Condition*

Finer mesh (Fig. 2) was used which are 0.8~1.25mm, in the areas more vulnerable to fatigue failure, in other areas relatively coarse (6.25~18.25mm) meshing was considered. For finite element modeling 8-noded continuum brick (hybrid) elements, C3D8H have been chosen from the available Abaqus 6.11 element library. As penalty method was used to impose the incompressibility constraint the method can sometimes lead to numerical difficulties; therefore, the fully integrated "hybrid" formulation elements have been used as per the recommendation of Abaqus 6.11 manual. A 25MPa vertical compressive loading along with 1/150 rad rotation was applied by displacement control method.

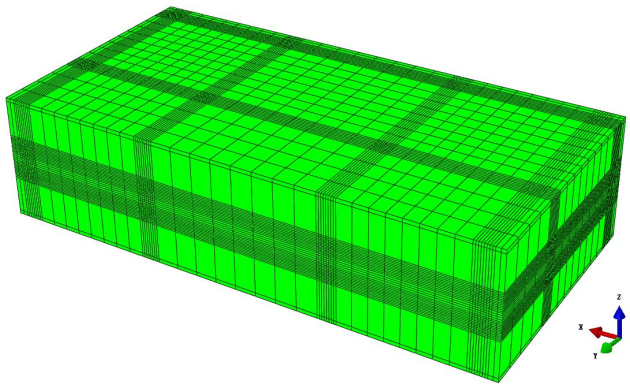

Figure 2. Finite Element Model of the Bearing Specimen

3.2 *FE Modeling and Loading Condition*

Rubbers not being able to be modeled as fully incompressible material, has been considered here as nearly incompressible. To avoid ill-conditioned system of equations caused by incompressibility feature of rubber, it was modeled adopting a penalty method (Simo and Taylor 1982) where the poison's ratio is considered in the range of 0.49~0.49995. The Yeoh Hyperelastic model used here is

$$U = C_{10}(\bar{I}_1 - 3) + C_{20}(\bar{I}_1 - 3)^2 + C_{30}(\bar{I}_1 - 3)^3 \qquad (1)$$

To model rubber under nearly incompressible environment the following volumetric relationship was already added with this Model in Abaqus

$$\frac{1}{D_1}(J^{el} - 1)^2 + \frac{1}{D_2}(J^{el} - 1)^4 + \frac{1}{D_3}(J^{el} - 1)^6 \qquad (2)$$

where D_i is called the relative compressibility and J^{el} is the elastic volume ratio. The value D_1 is related with the initial bulk modulus K_0, if $D_2 = D_3 = 0$ then $K_0 = 2/D_1$; the elastic volume ratio J^{el} relates to the total volume ratio, J, $J^{el} = J/J^{th}$ and the thermal volume ratio, J^{th} where J^{th} is given by $\mathbf{J}^{th} = (1 + \varepsilon^{th})$ Where ε^{th} is the linear thermal expansion strain. The bulk modulus value is very decisive to match the actual load-displacement relationship of rubber under high confinement and compressive loading. Equation (1) has been fitted for both compression and tension region using built in abaqus material evaluation tool. The determined parameters for both rubber materials are given in Table 2.

Table 2. Identified Material Parameters for Yeoh Model from Uni-axial test results

Parameter	C_{10} (MPa)	C_{20} (MPa)	C_{30} (MPa)
G8	0.3234	0.0160	7.59E-5
G12	0.4759	0.0151	1.29E-5

D_i is a coefficient in equation (2); on the basis of sequential trial and error based estimation to obtain the best agreement with the experimental results with Type-2 sample it has been found that 10 percent increment on the base value selected for D_1 can be used for D_2 and D_3 and it provides better agreement which are provided in Table 3 .

Table 3. Relative compressibility values used for the analysis

Parameter	D_1 (1/MPa)	D_2 (1/MPa)	D_3 (1/MPa)
G8	0.0025	0.0027	0.0030
G12	0.0025	0.0027	0.0030

4 LOAD-DISPLACEMENT RELATIONSHIP

All the bearings were subjected to a target compressive stress of 25 MPa corresponding to a vertical load of 1600 KN for pure vertical compressive loading and combined vertical compressive loading with a target rotation of 1/150 rad.

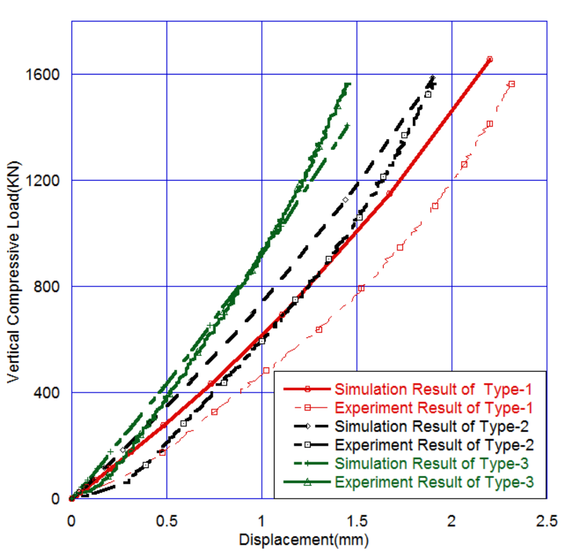

Figure 3a. Load-Displacement curves for vertical compressive loading (with rotation)

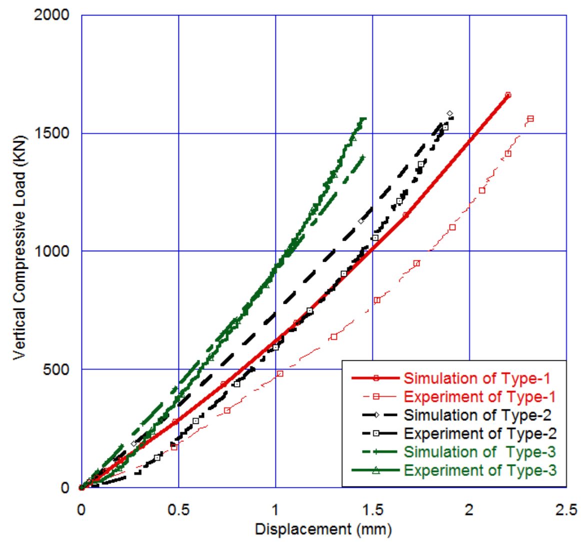

Figure 3b. Load-Displacement curves for vertical compressive loading (without rotation

Comparison of the numerical results with experimental ones (Figure 3a & Figure 3b) reveal that for both pure compression and compression with rotation cases stiffness increased with the increase in the size of the steel plate inside. As Type-1 has the shortest steel plate it has the lowest stiffness compared to the largest steel plate size which is inside the Type-3 bearing.

5 SHEAR STRESS AND STRAIN

Application of rotational displacement along with vertical compressive loading results in asymmetrical (Fig. 4a) distribution of shear stress with values increased in the direction of the rotation due to presence of vertical compressive loading applied earlier. However, on the opposite direction of the rotational displacement, stress concentration decreased slightly at the corners. The maximum shear stress for rubber was found in the internal rubber layers between the steel-rubber interfaces which are vulnerable to fatigue damage. The magnitude for the shear stress decreased with the increase in the internal steel plate size to a certain level.

Under the same loading condition shear strain distribution also becomes asymmetrical (Fig. 4b) and the intensity has been found to spread along the interfacial plane of rubber and steel. The magnitude of shear strain decreased with the increase in steel plate size with the exception for the traditional bearing in which the strain value increased (Fig.5).

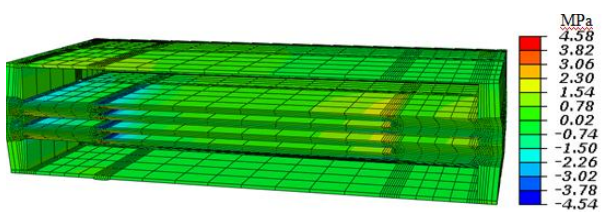

Figure 4a. Shear Stress Distribution

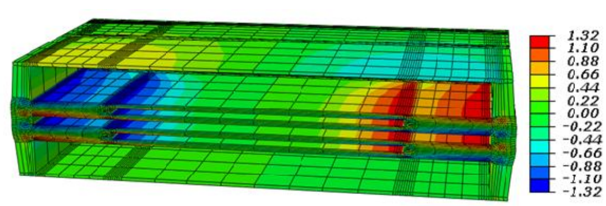

Figure 4b. Shear Strain Distribution

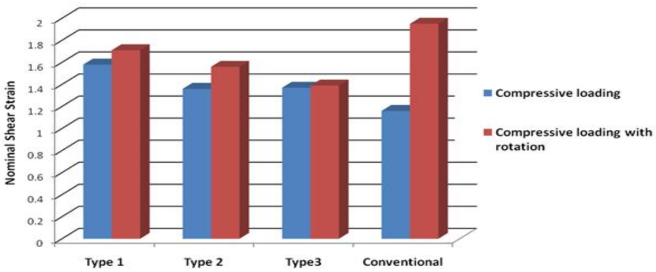

Figure 5. Comparison of Maximum Nominal Shear strain under different loading condition

6 CONCLUDING REMARKS

Responses for the three design types of laminated natural rubber bearings, having variable internal steel plate size subjected compression and rotation were simulated using a nonlinear finite element analysis technique. Natural rubber was modeled as Hyperelastic material with the Yeoh Hyperelastic model and as nearly incompressible material applying the penalty method. The Yeoh model has been found to be effective in defining the non-linearity of the rubber. The values for the relative compressibility in the Bulk modulus part was critical in getting good agreement with experimental results of the load displacement relationship as the bearings were under high confinement and compression.

While comparing the principal stress and strain distribution the concentration of shear stress and shear strain were found higher at the inside the steel plates and rubber interface. From fatigue durability point this locations are susceptible to damage. It has also been observed that the stress and strain concentration at the vulnerable location changes with the change in the internal steel plate size. In that respect, shortening the steel plate can be solution to increase rotational flexibility and better performance against fatigue damage.

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