Numerical study on the response of steel-laminated elastomeric bearings subjected to variable axial loads and development of local tensile stresses

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ABSTRACT

Steel-laminated elastomeric bearings are isolation devices which are used extensively in buildings, bridges, nuclear power plants and other structures. Accurate modelling of the behaviour of these devices is of great importance, as the integrity of isolated structures relies heavily on their response. For many years, steel-laminated bearings were designed based on the assumption that they are subjected to compressive and shear loads, as a result of the dead and the horizontal loads, i.e. wind and seismic loads, acting on the structure. It is only very recently that tensile stresses in bearings were studied, as it was observed that local and global tensile stresses might be developed in bearings under seismic excitations. Most importantly, tension within the elastomer might cause local cracks or, in extreme cases, rupture of the elastomer, which might lead to the loss of support of isolated structures. Yet only a few studies exist in the international literature with regard to response of these devices under combined axial and shear loads. The aforementioned gap in the knowledge and the identified rupture of the elastomer of bearings under tensile loads during recent earthquakes comprised the motivation for this research. In this context, this paper examines the response of steel-laminated elastomeric bearings under cyclic shear and variable axial loads and aims to better understand their behaviour with emphasis placed on the tensile stresses within the elastomer, their stiffness and dissipation capacity. Extensive numerical research was conducted with ABAQUS and the Ogden hyperelastic model was used for modelling the elastomeric material. The analyses showed that steel-laminated elastomeric bearings exhibit local tensile stresses, which alter significantly their stiffness and damping ratio. Most importantly, significant tensile stresses within the elastomer were observed locally, even when the bearings were subjected to a combination of shearing and compression.

Keywords: seismic isolation; steel-laminated elastomeric bearing; tensile stresses; stiffness; damping ratio; hyperelastic; Ogden

1. INTRODUCTION

Steel-laminated elastomeric bearings are common bearings that are used to isolate structures. Their use in structural applications dates in the late 1950s, but research and development of materials and design of the isolators continued over the years until today [1-2]. The application of steel-laminated elastomeric bearings for the seismic isolation of bridges [3] and buildings became more popular after the early 1990s, [4-5]. Bearings are used to accommodate movements of the structures, such as dynamic (e.g. seismic) displacements as well as static or quasi-static movements due to creep, shrinkage and thermal effects [6-9] thus transmitting negligible loads to critical structural components, such as bridge piers and foundations. Bearings undertake structural movements and vibrations due to the fact that their shear stiffness is relatively small, thus movements and vibrations are absorbed by shear deformations of the bearings and produces negligible reactions, whilst their stiffness under compressive loads is relatively high to support the weight of the structure [5].

Despite the fact that the current codes of practice describe the behaviour and provide guidelines for the modelling of the bearings, as well as prescriptions and limitations with regard to acceptable design limit states [10-17], only a few design guidelines and studies exist on steel-laminated elastomeric bearings subjected to tensile stresses when subjected to cyclic loading. However, very recent earthquakes in South America and Asia, the 1999 Chi-Chi earthquake in Taiwan, the 2010 Chile

Earthquake, the 2011 off the Pacific coast of Tohoku earthquake in Japan [18-21], revealed that bearings might be subjected to tensile stresses locally, even when the global response of the isolator is shearing and axial compression. Thus the design guidelines for isolation bearings must enhance the resilience of these components under cyclic loads [22-23] and especially under large tensile stresses that might cause cracks or rupture of the elastomer, the latter only in extreme design cases.

With regard to code provisions, BS EN 15129 [11] and EN 1337-3 [12] allow the development of tensile stresses within elastomeric bearings up to $2G$, where G is the shear modulus of the elastomer, and its values range between 0.55 MPa and 1.2 MPa. According to AASHTO [14], tensile stresses up to $2-3 G$ might be developed within the bearing, hence the limit value of tensile stresses that AASHTO [14] sets, is in the range of 2 to 3 MPa, assuming a typical value of G of 1 MPa. Similarly, the JRA [17] allows small tensile stresses in bearings, up to 2 MPa. In aseismic design code of China, the tensile stress is limited to 1 MPa [24]. Eurocode 8 Part 2 [10] restricts the development of tensile stresses within bearings under the design seismic combination. Based on the aforementioned codes, it is evident that the tensile response of bearings is a matter that has different design approaches and requires further investigation. Most importantly, none of the codes define whether the allowable tensile stresses refer to the global response of the bearing, i.e. global tension as described by Mitoulis [7], Tubaldi et al. [25] and Mitoulis et al. [26] for bridge bearings, or local tensile effects.

With regard to international literature, emphasis was placed on the shear and compressive response of the isolators under design basis earthquakes by performing numerical tests and experiments [7] [26-34], whilst less emphasis was placed on the tensile response of the isolators [4] [6] [31-38]. Additionally, Cardone & Perone [39] based their research on the assumption that there is no development of tensile stresses in the bearings. However, Stanton et al. [1] examined all possible deformations that the bearing can sustain. The latter research concluded that elastomeric bearings can undertake shearing, compression and rotations, but recommend that the isolators should not be subjected to significant tensile stresses. For design earthquakes, the influence that the earthquakes have on the mechanical properties of bearings (shear stiffness and damping ratio) will be relatively small, however stronger seismic motions and larger displacements change the bearing properties dramatically [27] [39-40]. Reliance of current design practice is based on the fact that elastomeric bearings are subjected to significant compressive loads due to the self-weight of the supported structure, thus the possibility of tensile loading is adequately low.

One of the first and comprehensive studies on the behaviour of rubber cylinders in tension was performed by Gent & Lindley [41]. This experimental research was completed almost a decade after the appearance of Mooney-Rivlin hyperelastic model [42-43] and before the appearance of Ogden hyperelastic model [44]. It was observed that when applying small tensile loads and after exceeding the theoretical yielding point, i.e. development of cavities within the rubber, internal cracks (cavities) were developed in all the specimens used. Nonetheless, rupture occurred only in samples of small thicknesses. Gent & Lindley [41] proved for the first time that there is damage in the internal compound of the elastomer when tensile stresses with the value of 2.75 MPa was imposed to it and this damage leads to severe degradation of the strength of the elastomer. Iwabe et al. [45] tested experimentally the effect of tension on steel-laminated elastomeric bearings. Tensile strains up to 100% were imposed to the bearing together with shear strains up to 200 %. The study concluded that increasing non-linear effects were observed for increased tensile strains, however bearings did not exhibit cavitation. However, even when pure tensile strain of 100 % of the thickness of the elastomer was imposed to the bearing, the rubber did not rupture, which indicates that bearings have high tensile capacity. Additionally, recent studies revealed that the tensile stiffness of bearings is important to describe the bearing response and thus the response of isolated structures. Also the bearing exhibits non-linear behaviour for tensile stresses larger than 1 – 2 MPa, whilst its tensile stiffness is approximately equal to 1/7 of the compressive one, based on the tangent stiffness measured near origin [24]. Nonetheless, design guidelines usually do not take into account the axial stiffness of the isolators or prescribe that the tensile stiffness is similar to the compressive one, indicating that the axial response of the elastomeric isolators is neither well understood nor studied.

This paper aims to better understand the behaviour of steel-laminated elastomeric bearings. This was achieved by defining the variation of important design properties of the isolators, i.e. stiffness and damping ratio, and also by identifying local tensile stresses when the isolators are subjected to large cyclic shear displacements and variable axial loads. The aforementioned loads correspond to shear

strains, ranging from 125 % to 375 %, whilst vertical loads range from 2 MPa tensile to 14 MPa compressive stresses. It is noted that the shear strain corresponds to shear displacements over the total thickness of the elastomer, hence not taking into account the thickness of the metal plates of the bearing. ABAQUS Ver. 6.13 [46] [47] [48] was used for the analyses and different boundary conditions, target displacements and axial loads were considered to cover a wide range of bearing applications on bridges. The hyperelastic Ogden material [44] was used for all the analyses.

2. VALIDATION OF THE NUMERICAL MODEL OF THE BEARING AND PARAMETRIC STUDY

2.1 Material Properties

The calibration of the models of steel-laminated elastomeric bearings analysed in this paper was based on the study of Ohsakiet al [36]. The latter numerical models were developed in ABAQUS and compared against results available in the literature [36] [47]. This calibrated numerical model was considered to be the reference of this study. Subsequently, the modelled bearings were subjected to shear and variable axial loads. The Ogden hyperelastic material model [44] was used for modelling the elastomeric layers of the reference bearings as it was found to be the most accurate model for elastomeric materials representing natural rubber. The hyperelastic material describes accurately the stresses, the strains that are developed within the elastomer and the energy dissipation (hysteresis) within the bearing. The Ogden strain energy density function is defined in Equation 1 below:

$$U = \sum_{n=1}^2 \frac{\mu_n}{\alpha_n} (\bar{\lambda}_1^{\alpha_n} + \bar{\lambda}_2^{\alpha_n} + \bar{\lambda}_3^{\alpha_n} - 3) + 4.5B(J^\beta - 1)^2 \quad (1)$$

In Equation 1, the hyperelastic parameters are $\mu_1 = 0.41 \text{ MPa}$, $\alpha_1 = 1.6$, $\mu_2 = 0.0012 \text{ MPa}$, $\alpha_2 = 6.2$ and $\beta = 1/3$. These values were obtained from experiments of a rubber bearing with variable pressure levels as for example in the paper of Bradley et al. [35]. Where J is the elastic volume ratio and $\bar{\lambda}_1, \bar{\lambda}_2, \bar{\lambda}_3$ are the deviatoric stretches, i.e. the principal values of right stretch tensor. The values of the shear modulus and the Poisson ratio are calculated as per the reference case and are described by Equations 2 and 3:

$$G = \alpha_1 \mu_1 + \alpha_2 \mu_2 \Rightarrow G = 0.66344 \text{ MPa} \quad (2)$$

$$\nu = \left(\frac{3B}{G_b} - 2 \right) / \left(\frac{6B}{G_b} - 2 \right) \Rightarrow \nu = 0.49989 \quad (3)$$

For this particular research, it is noted, that the Mullins' effect [49-50], which causes reduction of the bulk modulus of the elastomer during the first cycles of the bearing loading, was not taken into account, and the bearings were considered scragged. This assumption was based on the fact that bridge bearings are subjected to continuous cyclic movements due to the thermal expansion and contraction of the deck. It is noted that Mullins effect occurs predominantly during the first cycle of loading, whilst the reduction of the bulk modulus of the elastomer is incrementally smaller during the subsequent cycles, up until the stabilization in the hysteresis [49].

2.2 Geometry and loading

Figure 1 and Table 1 describe in detail the geometry of the reference bearing. This model is referred hereinafter as Non Linear bearing and denoted as *NL*. The circular bearing has a diameter of 700 mm. Circular plates of diameter 1000 mm were used as the top and bottom anchor plates of the bearing. The steel-laminated elastomeric bearing numerical model has a total of 30 layers of elastomer, 29 steel shims and two anchor plates. The total thickness of the elastomer is 120 mm i.e. 30 elastomeric layers of 4 mm thickness each. The total thickness of the steel shims is 89.9 mm i.e. 29 steel shims of 3.1 mm each. The two top and bottom anchor plates have a thickness of 28 mm each. Thus, the total height of the reference bearing is 120mm+ 89.9mm+ 2x28mm= 265.9mm. The diameter of the elastomeric

layers and steel shims is 700 mm and the diameter of the anchor plates is 1000 mm. At the centre of the reference bearing there is a hole with a diameter of 15 mm. The elastomeric layers and steel shims were discretised with linear wedge elements of type C3D6. Geometric non-linearities are incorporated in the analysis.

(Figure 1)

Figure 1. Meshing of the reference NL^C elastomeric bearing in ABAQUS: (a) side view and bottom anchor plate boundary conditions, (b) three dimensional model, (c) section.

(Table 1)

Table 1. Geometry of the reference bearing NL^C .

The bottom anchor plate of the model is fixed. Shear displacement of 450 mm and simultaneous axial pressure is imposed to the top anchor plate of the bearing. Initially, the bearing was subjected to one full cycle of shear corresponding to a shear strain of 375 %, thus the shear displacement is 450 mm. Figure 2 shows the comparison of the results of the numerical model analysed in this paper against the available results in the literature [36]. It is observed that the reference bearing (grey diagram) reproduces accurately the force-deformation diagram of the available numerical and experimental results of previous studies (dashed lines) [36]. Also, the experimental results were modelled with acceptable accuracy for both the loading and the unloading of the bearing. This reference model was used in the parametric study presented in the following sections of this paper.

(Figure 2)

Figure 2. Validation of the reference bearing model against the available numerical and experimental results.

2.3 Parametric study on the response of steel-laminated elastomeric bearings

Variable axial loads, compressive or tensile, ranging from 2 MPa (tensile) to -14 MPa (compressive) with the intermediate values of 0, -2, -5 and -10 MPa and shear strains of 375 % are applied to the reference bearing to identify the variation of its behaviour on the basis of global response parameters (stiffness and dissipation capacity) as well as local effects, i.e. concentration of tensile stresses. During the analyses it was evident that the boundary conditions played an important role with regard to tensile stresses that were developed within the elastomer. Thus, apart from the variation of the axial load, two different boundary conditions were considered: one considering that the bearing is fixed at the bottom, but free to rotate at the top and a second one that had $UX=UY=UZ=RX=RY=RZ=0$ at the bottom, i.e. fixed, and $RX=RY=RZ=0$ at the top, i.e. the upper anchor plate rotation is restricted and remains parallel to the bottom one, but it is free to move along X, Y, Z axes. The boundary conditions chosen in this study also reflect the two cases that are met in practical applications, where the bearings might exhibit significant rotations, thus allow for relative rotations of the upper and the lower anchor plates of the isolator or the isolator exhibits negligible rotations, thus the upper anchor plate displaces almost parallel to the bottom one. In real applications the rotation of the isolator should be kept within allowable limits [1], thus the cases analysed in this paper provide an envelope of the prospected responses of isolators.

Table 2 shows the loading conditions that were analysed, i.e. the axial load, either tension or compression together with a target shear strain of 375 %. This shear strain was chosen in order to better understand the response of the isolators when subjected to large shear displacements, as bearings exhibit instabilities, e.g. buckling for larger shear strains. On the other hand, the behaviour of isolators under tensile stresses was also studied. In particular a maximum tensile stress of 2 MPa was applied to the bearings simultaneously with shear strain of 375 %.

(Table 2)

Table 2. Analyses of the reference bearing for variable axial loads, different boundary conditions, shear strain 375 % and different number of cycles of loading - unloading.

With regard to number of loading cycles, one full cycle of loading-unloading at ± 375 % shear strain was imposed to the isolator. To obtain the hysteresis loops from the analyses and to capture the damping properties of the bearing, the hysteretic parameters of ABAQUS were used. The hysteretic parameters with their values derived from the paper of Bergström & Boyce [51]. The Stress Scaling Factor, which influences the damping ratio of the isolators, was taken 1.6 based on the research of Bergström & Boyce [51]. This factor gives reliable results for low-damping rubber bearings, having a damping ratio smaller than 10 % [10]. The additional hysteretic parameters which were taken into consideration for this study, and their values, obtained from the aforementioned paper are as follows: Creep Parameter $A = 0.56$, Effective Stress Exponent $m = 4$ and Creep Strain Exponent $C = -1$. All these parameters are unitless. It is noted that, based on reference [51], the hysteresis loop which is produced due to the cyclic loading is not related to the Mullins effect. Also, analyses were conducted for a total of two cycles, shown in Figure 3b, however the results were found to be identical as the bearing force displacement curves followed the same loading path, i.e. the one of the first cycle. The analyses herein assume that the elastomer exhibits no cavitation.

3. RESPONSE OF ELASTOMERIC BEARINGS AND LOCAL TENSILE STRESSES

3.1 Influence of the axial load on the stiffness and damping of the bearing

From figure 3a it is observed that there is a reduction of the secant stiffness of the bearing when the compression is increased. Generally, the higher the axial pressure that is imposed the smaller the value of horizontal reaction that is developed at the bottom anchor plate, i.e. the smaller the stiffness for the same target displacement. The former observation is in line with previous studies [52]. However, this was found to be the case when the target displacements are larger than 200 mm, i.e. shear strains larger than 167 %. For smaller shear strains, the secant stiffness was found to be initially increased, then decreased and then increased again for larger shear strains when the vertical compression is 14 MPa (NL_6), whilst the behaviour of the bearing was found to be almost linear when the compression is relatively low, i.e. up to 2 MPa (NL_3).

With regard to the behaviour of the bearing for the target shear strain of 375 %, in combination with free movement of the upper anchor plate (i.e. the upper anchor plate is free to rotate, $UX, UY, UZ, RX, RY, RZ \neq 0$), the shear stiffness undergoes negligible reduction when the axial compression increases from zero (NL_2) to 2.0 MPa (NL_3) and from 2.0 MPa (NL_3) to 5.0 MPa (NL_4), 12.9 % when the axial load increases from 5.0 MPa (NL_4) to 10 MPa (NL_5) and 17.5 % when the axial load increases from pressure 10 MPa (NL_5) to 14 MPa (NL_6). It is noted that the stiffness for the aforementioned comparisons corresponds to the secant stiffness at the maximum shear strain of the bearing, i.e. 125%, 250% and 375%. Based on the hysteresis loops shown in Figure 3a and 3b the damping ratio ζ was calculated based on Equation 4 [5]:

$$\zeta = \frac{A}{2 * \pi * K_{eff} * D^2} \quad (4)$$

In Equation 4, A is the area of the hysteresis loop, K_{eff} is the effective stiffness of the bearing measured at the maximum target displacement of 150 mm, 300 mm and 450 mm, respectively for the shear strains of 125 %, 250 % and 375 %, and D is the displacement amplitude. Based on the results of the numerical model, it was found that the damping ratio increases by 29 % when the axial load increases from compression 5 MPa (NL_4) to compression 10 MPa (NL_5).

(Figure 3)

Figure 3. Response of the reference steel-laminated elastomeric bearing for variable axial loads (shear strain 375 %) for (a) one cycle of loading (NL_1 - NL_6) and (b) two cycles of loading (NL_{10} - NL_{15}).

Additional analyses were conducted to assess the influence of local tensile stresses on the response of the bearing. Taking into account that acceptable tensile stresses are of the order of 2-3 MPa, a uniform tensile stress of 2 MPa (NL_1) was applied axially to the isolator together with a shear strain of 375 %. The stiffness and the damping of the isolator under tension (2 MPa) was then compared to the response of the bearing under compression, the latter having a compression of 2 MPa (NL_3). Also, the analyses only considered global (also known as hydrostatic) stresses on the bearing, i.e. uniform tensile or compressive stresses.

Figure 4 shows the force-displacement curves of the same bearing when the latter is being subjected to either tension or compression together with maximum shear strains of 375 % and the upper anchor plate is free to rotate (i.e. UX, UY, UZ, RX, RY, RZ=0 for the upper anchor plate). The figure shows that the shear stiffness and damping ratio of the isolator are not influenced significantly when low axial strains (either tensile or compressive) are imposed on it. For example, when the axial load is tensile 2 MPa (NL_1) the shear stiffness is 2398 kN/m. The corresponding stiffness when axial compression of 2 MPa (NL_3) is applied is 2285 kN/m thus the increase in the stiffness is approximately 5 %, which is considered to be within the expected variation of the properties of the isolator.

(Figure 4)

Figure 4. Shear force-displacement response of the steel-laminated elastomeric bearings for axial tension (2 MPa) and axial compression (2 MPa) (shear strain is 375 %).

Additionally, buckling is taken into account, due to large deformation, but no buckling has been observed, based on the calculation process that is proposed in the BS EN 11529:2009 [11] and has been used in order to validate the fact that no buckling is developed during the analyses.

3.2 The effect of boundary conditions on the stiffness and the damping of the bearing

As it was mentioned before, the boundary conditions of bearings with regard to rotations of the anchor plates vary significantly based on the response of the structural components upon which the bearings are anchored. For example the isolation bearing on buildings have a predominantly translational movement, whilst rotations are negligible. However, bearings used on piers to support bridge decks might exhibit significant rotations due to the deflection of the piers and the rocking of the foundation [53]. Figures 5, 6, and 7 illustrate the bearing responses for different boundary conditions of the bearings, i.e. when the top anchor plate is free to rotate or its rotations are restricted.

More specifically, Figures 5, 6 and 7 show the hysteresis loops of the bearings subjected to shear loading and axial compressive stresses of 5 MPa (NL_4 .- NL_7), 10 MPa (NL_5 .- NL_8) and 14 MPa (NL_6 .- NL_9) correspondingly. From these figures, it is evident that the stiffness of the bearing is increased when the top anchor plate is fixed, which is reasonable based on the fact that additional restraints increase the stiffness of the isolator. What is of interest in this case is the fact that the shear stiffness of the isolator is increased by 10.2 % when the anchor plate rotation is restricted and the compressive load is 5 MPa, whilst the increase in the stiffness is 9 % and 32.1 % when the compression of the bearing is 10 MPa and 14 MPa respectively. The latter observation is important as the stiffness of the isolator is of great importance to the design of structures subjected to static or dynamic loads. For example, the design of bridge abutments, piers and foundations is based on the period of the isolated structure, whilst the forces transmitted from the bearings to the substructures are the ones used for selecting the reinforcements and the foundation size. Additionally, the design of the expansion joints is dependent on the displacements of the deck and thus the stiffness of the isolation system.

With regard to damping, the numerical model shows that the damping ratio of the bearing is decreased when the rotation of the upper anchor plate is restrained. When the axial pressure is 5 MPa there is a negligible decrease of its damping ratio when the top anchor plate rotation is fixed as opposed to the case where the top anchor plate is free to rotate. The corresponding decreases when the axial load is

10MPa or 14 MPa are 27.9 % and 42.3 % respectively. Thus, the boundary conditions of the isolator seem to influence significantly both the stiffness and the damping of the isolator. Also, it seems that the higher the vertical load on the isolator the more important is the role of the boundary conditions of the isolator, as both its stiffness and damping might change drastically, thus affecting the overall structural response of the isolated structure.

Another notable effect of the bearing boundary condition is the fact that the response of the bearing in terms of shear-force displacements, deviates significantly from the linear behaviour when the boundary conditions change. For example, Figure 5 shows that when the rotation of the upper anchor plate of the bearing is restrained the isolator has a response that is essentially linear up until the maximum displacement of 450 mm. Contrarily, the behaviour of the isolator is different when the bearing upper anchor plate is free to rotate. In the latter case, the bearing stiffness decreases after the displacement of 240 mm, i.e. after a shear strain of 200 % is applied, whilst its stiffness increases again at higher shear strains, i.e. 250 % that corresponds to shear displacement of 300 mm. This behaviour was observed before based on shear tests against which numerical models were validated [25].

(Figure 5)

Figure 5. Shear force-displacement response of the steel-laminated elastomeric bearings for different boundary conditions (compression 5 MPa and shear strain 375 %).

(Figure 6)

Figure 6. Shear force-displacement response of the steel-laminated elastomeric bearings for different boundary conditions (compression 10 MPa and shear strain 375 %).

(Figure 7)

Figure 7. Shear force-displacement response of the steel-laminated elastomeric bearings for different boundary conditions (compression 14 MPa and shear strain 375 %).

3.3 Development of local tensile stresses

For identifying the potential tensile stresses (noted as S33 in the following figures) within the bearing, additional analyses were performed with the reference bearing considering again variable boundary conditions (free or restraint rotation of the upper anchor plate) and a range of shear strains i.e. 125 %, 250 % and 375 %. The analyses performed are shown in Table 3 (analyses 16 to 21). The axial load was kept constant in this case and equal to 10 MPa, which is considered to be a relatively high compressive load for bridge bearings. It is recognised that the maximum compressive stresses chosen, i.e. 10 and 14 MPa, are relatively large for bridge applications and for isolated structures in general. However, Eurocode 8 Part 2 [10] allows maximum shear strains, due to vertical compression of the isolator, up to 2.5. Thus extreme earthquake excitations on bridges, which might lead to large axial loads and/or to potential local tensile stresses, are analysed in this paper, with the aim to better understand how these loads might affect the performance of the isolators.

(Table 3)

Table 3. Analyses of the reference bearing for variable shear strains and boundary conditions (axial compressive load 10 MPa).

Figures 8-13 show vertical sections along the diameter of the reference circular bearing with the same axial compressive load of 10 MPa and variable shear strains and boundary conditions as described by Table 3. It is noted that the values of the numerically calculated stresses within the elastomeric bearings did not consider the potential of local cavitation and hence the stresses are hypothetical in the sense that the elastomer remains elastic. Figures 8 and 9 show the vertical sections of the reference bearing at shear strain 125 % i.e. shear displacement of 150 mm and upper anchorplate free to rotate (NL_{16}) and with rotational restraint (NL_{17}) respectively. Subsequently, Figures 10 and 11 illustrate the sections of the reference bearing subjected to shear strain of 250 % i.e. shear displacement of 300

mm and variable boundary conditions (NL_{18} , NL_{19}). Figures 12 and 13 show vertical sections of the reference bearing with shear strain of 375 % i.e. shear displacement of 450 mm and variable boundary conditions (NL_{20} , NL_{21}). Thus, the upper plate remains horizontal and parallel to the bottom plate in Figures 9, 11 and 13, whilst the upper plate rotates in Figures 8, 10 and 12.

It is observed that when the shear strain that is imposed to the bearing is 125 %, then the upper anchor plate exhibits a rotation of 2.4 degrees. The corresponding rotation when the shear strain is 250 %, which is shown in Figure 11, is 3.6 degrees and 4.4 degrees for shear strain of 375 %, shown in Figure 12. The grey areas that are shown in Figures 8-13 are areas where local tensile stresses are developed. It is observed that these areas are becoming more pronounced when the shear displacement increases, despite the fact that the external axial load was a considerable compressive load of 10 MPa. Moreover, the distribution of the tensile stresses varies significantly for the two different boundary conditions considered for the top anchor plate, with the local tensile stresses being significantly higher when the upper anchor plate is free to rotate. The latter explains the rotation limits proposed in design guidelines of steel laminated rubber bearings. Also, local tensile stresses become higher when the shear displacement increases. For example, the maximum local tensile stress on Figure 9 is 1.46 MPa and this corresponds to a shear strain of 125 %, whilst the local tensile stress is 2.14 MPa when the shear strain is 375 %. Finally, the comparison between Figures 8, 10 and 12 with the Figures 9, 11 and 13 shows that in the latests (i.e. at the cases where there is restraint of the rotation of the upper anchor plate), there is development of local tensile stresses at the top left and bottom right areas of the bearing with concentration of compressive stresses at the centre of it, while at the case where the upper anchor plate is free to rotate, there is concentration of local tensile stresses at the right area of the bearings with concentration of compressive stresses at the left area of the bearing. When it comes to small shear strain of 125 % with pressure of 10 MPa and the top anchor plate free to rotate, there is development of tensile stresses at the centre of the bearing with development of compressive stresses at the perimeter of the bearing. This is a condition which appears due to the flexibility of the upper anchor plate.

(Figure 8)

Figure 8. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 125 % and upper layer of the reference bearing free to rotate (NL_{16}) (vertical section at bearing diameter).

(Figure 9)

Figure 9. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 125 % and application of rotational restraint of the upper layer of the reference bearing (NL_{17}) (vertical section at bearing diameter).

(Figure 10)

Figure 10. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 250 % and upper layer of the reference bearing free to rotate (NL_{18}) (vertical section at bearing diameter).

(Figure 11)

Figure 11. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 250 % and application of rotational restraint of the upper layer of the reference bearing (NL_{19}) (vertical section at bearing diameter).

(Figure 12)

Figure 12. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 375 % and upper layer of the reference bearing free to rotate (NL_{20}) (vertical section at bearing diameter).

(Figure 13)

Figure 13. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 375 % and application of rotational restraint of the upper layer of the reference bearing (NL_{21}) (vertical section at bearing diameter).

Figure 14 shows the position of the top, middle and bottom rubber layer which is used in order for the development of local tensile stresses to be illustrated. Figures 15a, b and c which depict horizontal sections of the top, middle and bottom rubber layer when the upper layer is free to rotate, by emphasizing to the areas where the tensile stresses are developed, enhance the observation that large tensile stresses are developed within the bearing. These areas are depicted with grey colour. In Figure 15a, where the shear strain imposed is 125 %, there is development of compressive stresses at the upper half of the bearing (y-axis is the direction of the imposed shear strain), while tensile stresses are developed at the centre of the bearing. When the shear strain is increased to 250 % then there is development of tensile stresses in the top, middle and bottom rubber layer, with values larger than 10 MPa, which are concentrated at the bottom half of the bearing (i.e. at the opposite direction of the imposed shear strain). Finally, when the shear strain is increased to 375 %, extreme local tensile stresses are developed in the bearing. The tensile stresses are developed within the area, where there is rotation of the bearing (right hand side in Figures 10 and 12) and furthermore, the tensile stresses that are developed within the body of the elastomer are higher at the boundaries of the bearing.

(Figure 14)

Figure 14. Three-dimensional view of the bearing indicating the position of the rubber layers shown in figures 15 and 16 below.

(Figure 15)

Figure 15. Axial stresses of the bearings at horizontal sections at the top, middle and bottom rubber layer. Gray areas indicate tensile stresses. Compressive load 10 MPa and upper layer of the reference bearing free to rotate, shear strain: (a) 125 % (NL_{16}), (b) 250 % (NL_{18}), (c) 375 % (NL_{20}).

Nonetheless, when a rotational restraint was applied on the upper anchor plate of the bearing, then there is not development of large tensile stresses towards the edges of the bearing. Figures 16a, b and c depict horizontal sections of the top, middle and bottom rubber layer of the reference bearing when the shear strains that are imposed to it are 125 %, 250 % and 375 % respectively and there is rotational restraint of the upper layer. Based on these figures, development of compressive stresses is attained in the areas closer to the centre of the bearing. However, tensile stresses were observed at the edges of the rubber layer which do not exceed 1.70 MPa. Thus, the boundary conditions and the shear strain of the bearing influences strongly both the magnitude and the distribution of the tensile stresses within the elastomeric bearing.

(Figure 16)

Figure 16. Axial stresses of the bearings at horizontal sections at the top, middle and bottom rubber layer. Gray areas indicate tensile stresses. Compressive load of 10 MPa, application of rotational restraint of the upper layer, shear strain: (a) 125 % (NL_{17}), (b) 250 % (NL_{19}), (c) 375 % (NL_{21}).

4. CONCLUSIONS

A numerical study was performed to better understand the behaviour of steel-laminated elastomeric bearings under variable (tensile and compressive) axial loads, boundary conditions and target shear strains. A hyperelastic material model (Ogden) was used to model the behaviour of the elastomer and was calibrated against numerical and experimental results available in the literature. Emphasis was placed on the stiffness and the dissipation capacity of the isolators and the local tensile stresses which are developed within the bearing. The numerical study on ABAQUS came up with the following conclusions:

- An increase of the imposed compression leads to a significant decrease of the shear stiffness of the isolator. When the compression on the bearings increased from 5 MPa to 10 MPa the stiffness was reduced by approximately 13 %. The opposite was found to be valid for the dissipation capacity of the isolator, as the damping ratio of the isolator was increased by 29 % when the compressive stress was increased from 5 MPa to 10 MPa.
- The influence of different boundary conditions on the behaviour of the bearing was examined on the basis of two cases that were deemed to provide an envelope of the anticipated boundary conditions, i.e. free rotation of the anchor plates of the isolator or restricted rotations of the isolator. The numerical study showed that the rotational restraint of the bearing leads to higher shear stiffness and smaller damping ratio. More specifically, under the same axial compressive stress (10 MPa) and for the same target shear strain 375 % the bearing that has its anchor plates restricted to rotate was found to have shear stiffness 9 % larger and damping ratio approximately 27.9 % smaller than the bearing that was free to rotate.
- Development of local tensile stresses was observed within the analysed bearing, despite the fact that the external load on the bearing was global shearing and axial compression. Tensile stresses exceeding 5 MPa were found to be developed within the elastomer when the bearing was subjected to shear strains larger than 125 % and to vertical compressive stress of 10 MPa, whilst allowing the bearing to rotate freely, i.e. the bearing has no rotational restraints. However, the latter case (i.e. free bearing rotation) is not common in practical applications, where the two anchor plates are expected to exhibit minimal relative rotations. The analysis of the bearing when its anchor plates remained parallel throughout the analysis (rotations restricted) yielded maximum local tensile stresses smaller than 2 MPa. Thus providing designs where bearings exhibit minimal rotations minimise the potential development of adverse local tensile effects.

What is deemed to be important in order to accurately model, predict the behaviour and properly design isolated structures with steel-laminated elastomeric bearings is to better understand the response of the isolators under variable axial loads and different boundary conditions. This is related to the need for accurate predictions of both the stiffness and the damping of the isolators and thus the behaviour of the isolated structure. The actual behaviour of the isolators under these local tensile effects is not entirely understood or addressed to date.

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FIGURES

Figure 1. Meshing of the reference NL^C elastomeric bearing in ABAQUS: (a) side view and bottom anchor plate boundary conditions, (b) three dimensional model, (c) section.

Figure 2. Validation of the reference bearing model against the available numerical and experimental results.

(a)

(b)

Figure 3. Response of the reference steel-laminated elastomeric bearing for variable axial loads (shear strain 375 %) for (a) one cycle of loading (NL_1 - NL_6) and (b) two cycles of loading (NL_{10} - NL_{15}).

Figure 4. Shear force-displacement response of the steel-laminated elastomeric bearings for axial tension (2 MPa) and axial compression (2 MPa) (shear strain is 375 %).

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Figure 6. Shear force-displacement response of the steel-laminated elastomeric bearings for different boundary conditions (compression 10 MPa and shear strain 375 %).

Figure7. Shear force-displacement response of the steel-laminated elastomeric bearings for different boundary conditions (compression 14 MPa and shear strain 375 %).

Figure 8. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 125 % and upper layer of the reference bearing free to rotate (NL_{16}) (vertical section at bearing diameter).

Figure 9. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 125 % and application of rotational restraint of the upper layer of the reference bearing (NL_{17}) (vertical section at bearing diameter).

Figure 10. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 250 % and upper layer of the reference bearing free to rotate (NL_{18}) (vertical section at bearing diameter).

Figure 11. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 250 % and application of rotational restraint of the upper layer of the reference bearing (NL_{19}) (vertical section at bearing diameter).

Figure 12. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 375 % and upper layer of the reference bearing free to rotate (NL_{20}) (vertical section at bearing diameter).

Figure 13. The axial stresses within the bearing for compressive load of 10 MPa, shear strain 375 % and application of rotational restraint of the upper layer of the reference bearing (NL_{21}) (vertical section at bearing diameter).

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TABLES

Table 1. Geometry of the reference bearing NL^C .

	notation (unit)	value
diameter of the elastomer	D_r (mm)	700
diameter of the anchor plate	D_{AP} (mm)	1000
diameter of the hole	D_h (mm)	15
area of the elastomer layer	A_b (mm ²)	384845
total height of the bearing	T (mm)	265.9
elastomer layer thickness	t_r (mm)	4
number of elastomeric layers	n_r	30
total elastomer thickness	T_r (mm)	120
single steel shim thickness	t_s (mm)	3.1
number of steel shims	n_s	29
total steel shim thickness	T_s (mm)	89.9
single anchor plate thickness	t_{AP} (mm)	28
number of anchor plates	n_{AP}	2
total anchor plate thickness	T_{AP} (mm)	56

Table 2.Analyses of the reference bearing for variable axial loads, different boundary conditions, shear strain 375 % and different number of cycles of loading - unloading.

No#	axial load (MPa)	restraint rotation of the top anchor plate	cycles of loading - unloading
NL_1	2	No	1
NL_2	0	No	1
NL_3	-2	No	1
NL_4	-5	No	1
NL_5	-10	No	1
NL_6	-14	No	1
NL_7	-5	Yes	1
NL_8	-10	Yes	1
NL_9	-14	Yes	1
NL_{10}	2	No	2
NL_{11}	0	No	2
NL_{12}	-2	No	2
NL_{13}	-5	No	2
NL_{14}	-10	No	2
NL_{15}	-14	No	2

*NL: Non-Linear bearing model

Table 3.Analyses of the reference bearing for variable shear strains and boundary conditions (axial compressive load 10 MPa).

No#	shearstrain/ displacement(mm)	upper anchor plate restraint?
NL_{16}	125% / 150	No
NL_{17}	125% / 150	Yes
NL_{18}	250% / 300	No
NL_{19}	250% / 300	Yes
NL_{20}	375% / 450	No
NL_{21}	375% / 450	Yes

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NL_7	-5	Yes	1
NL_8	-10	Yes	1
NL_9	-14	Yes	1
NL_{10}	2	No	2
NL_{11}	0	No	2
NL_{12}	-2	No	2
NL_{13}	-5	No	2
NL_{14}	-10	No	2
NL_{15}	-14	No	2

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NL_{21}	375 % / 450	Yes

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