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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.

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

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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 cavitation 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 2*G*, 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 2–3 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 and 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 and 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 and 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. Nevertheless, 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 [46–48] 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 Ohsaki et 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 Eq. (1) below:

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

In Eq. (1), the hyperelastic parameters are $\mu_1 = 0.41$ MPa, $\alpha_1 = 1.6$, $\mu_2 = 0.0012$ 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 Eqs. (2) and (3):

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