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Finite element study of the effect of support rotation on the horizontal behavior of elastomeric bearings

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ABSTRACT

Laminated elastomeric bearings are used widely in both seismic and non-seismic structural engineering applications. The behavior of these bearings under pure loading (compression, shear, or bending) and under combined compression–shear loading has been studied at various levels in previous studies. However, very few studies have considered the behavior of elastomeric bearings under combined loading that includes rotation, and, to the best of the authors' knowledge, there has been no previous study on the effect of rotation on the lateral stability of elastomeric bearings. In bridge applications and some novel seismic isolation applications, e.g., isolation of high-rise buildings and mid-height isolation, it is possible for elastomeric bearings to experience rotation, the effect of which is not well understood. This paper studies the effect of rotation on the horizontal behavior of elastomeric bearings using 3D Finite Element Analysis (FEA). It is observed that constitutive modeling assumptions can have a notable influence on the results, especially at low vertical pressure where the critical shear strain is large. Support rotation does not affect the critical displacement appreciably, but it significantly affects the critical shear force. It is observed that support rotation becomes important for bearings with low second shape factor, even if their first shape factor is large.

1. Introduction

Multilayer elastomeric bearings are used extensively in bridge applications [1–4] to accommodate deformations associated with thermal expansion/contraction, traffic loads and construction misalignment, and to reduce the effects of earthquake loads on the bridge. Elastomeric bearings are also the most commonly used type of seismic isolation device in building applications ([5–8], among others and references reported herein). Isolation involves the introduction of a horizontally flexible layer that in effect decouples the superstructure from the horizontal seismic excitation. Conventional elastomeric bearings are made of layers of natural or synthetic rubber (often filled with various additives to enhanced their damping properties) interleaved with steel reinforcing plates (shims). Thick steel end plates are used to bolt the bearing to the superstructure and substructure. The horizontal shims restrict the lateral bulging of the rubber and provide vertical and rotational stiffness but do not affect the bearing's large horizontal flexibility. Early studies [9,10] showed that elastomeric bearings under combined axial and horizontal loads behave nonlinearly and, when they undergo large lateral displacements, they may experience a significant decrease in critical axial-load capacity. The behaviour of elastomeric bearings of various geometries subjected to pure bending was studied by Stanton and Roeder [1], Chalhoub and Kelly [11], Stanton et al. [12], and Kelly and Konstantinidis [7], among others, who developed expressions for the bending rigidity, a property that plays an important role in the estimate of the buckling load of a bearing. However, nearly all previous experimental and analytical studies investigating the behavior of elastomeric bearings under combined shear and compression were conducted under the assumption of zero top and bottom support rotation. This assumption is in many cases reasonable because the presence of rigid structural elements above and below the bearing prevent it from experiencing rotation at the supports. There are, however, several scenarios where it is possible for an elastomeric bearing to experience rotation at its supports, together with compression and shear. Ohsaki et al. [13], who investigated the dynamic response of a base-isolated 10-story reinforced-concrete frame building using 3D FEA, noted that the elastomeric bearings experienced rotation at their supports. In applications such as isolation of high-rise buildings or mid-height isolation [14], the effect of rotation may be significant. The effect of rotation may also be important in bridge applications, where the bearings

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can experience rotation due to flexure of the bridge deck above the bearing or the piers below. Because of its geometric nonlinearity, the problem of an elastomeric bearing under combined shear, axial and bending actions is not amenable to superposition of existing solutions for simple shear, pure axial and pure bending—even under the assumption of linear elasticity. This study aims to fill in the knowledge gap that currently exists by better understanding and quantifying the response of elastomeric bearings under combined loading that includes rotation.

The determination of the lateral stability limit of elastomeric bearings is based on an extension of Euler buckling load theory proposed by Haringx [15]. This linear theory assumes a bearing to be a homogenous, isotropic column that behaves as a rubber rod. Gent [16] investigated the decrease in the horizontal stiffness of rubber bearings with increasing axial load. Stanton et al. [17] extended the theory to account for the effect of axial shortening and provided experimental verification. Experimental tests on the stability of seismic isolation elastomeric bearings under quasi-static loading were conducted by Buckle and Kelly [9]. Buckle and Liu [18] carried out an experimental investigation to determine the critical buckling load of elastomeric bearings and proposed a formula based on the so-called *overlapping area method* to estimate the critical load, which is used in practice nowadays; although further experimental investigation showed this formula to be overly conservative, especially at lateral displacements equal to the bearing diameter, or width [19–21]. Sanchez et al. [21] carried out an experimental study on the stability of elastomeric bearings under quasi-static and dynamic loading. Two quasi-static and one dynamic methods were used. The first method followed the conventional method, where a bearing is held at a fixed horizontal displacement while the axial load is increased until the critical load is obtained. In the second method, the bearing was loaded under a constant axial load, while the horizontal displacement was increased until the instability point was observed. It was noted that the second method proved to be accurate and more direct in obtaining the critical load. The third method evaluated the dynamic stability of a group of elastomeric bearings supporting a rigid frame using shake table testing.

Besides experimental investigations, there have been several analytical studies on the stability of elastomeric bearings. Koh and Kelly [22] proposed a simple mechanical model including both shear and flexural deformations to study the stability of elastomeric bearings. They compared the results of the model to experimental results for natural rubber bearings and showed that the model captured the behavior with good accuracy. Koo et al. [23] modified the Koh–Kelly model by using an instantaneous apparent shear modulus obtained from test results instead of a constant shear modulus value. Nagarajaiah and Ferrell [24] extended the Koh–Kelly model to include large displacements. They showed that the critical load and horizontal stiffness decreases with increasing lateral displacement. Iizuka [25] developed a model by introducing finite deformation and nonlinear springs into the Koh–Kelly model. The model is shown to accurately capture the characteristics of elastomeric bearings, such as hardening, load deterioration, and buckling phenomena, by comparison to experimental results. Three-dimensional models using multiple shear springs at mid-height and a series of axial springs at the top and bottom were proposed by Yamamoto et al. [26] for circular bearings and Kikuchi et al. [27] for rectangular bearings. Han and Warn [28] conducted a sensitivity analysis on prior models using FEA and proposed an alternative model which does not rely on experimentally calibrated parameters. This model includes a series of vertical springs with a simple bilinear constitutive relationship. The vertical springs replace the rotational spring that was used in the Koh–Kelly model. Vemuru et al. [29] showed that the Nagarajaiah-Ferrell model, which was based on quasi-static tests, overpredicts the stiffness degradation beyond the stability point. They modified the Nagarajaiah-Ferrell model by incorporating higher order displacement terms in the rotational spring. The resulting model was shown to be able to characterize the dynamic behavior of bearings more accurately than previous models, particularly beyond the instability point. In another study by Vemuru et al. [30], a 3-DOF variant of the Nagarajaiah-Ferrell model was introduced, capable of capturing the vertical behavior more accurately.

FEA has become a common approach for understanding various aspects of the behavior of rubber bearings. The first study on the stability of elastomeric bearings using FEA was conducted by Simo and Kelly [31]. Recently, Warn and Weisman [32] conducted a parametric study to investigate the effect of geometry on the critical load of rubber bearings using 2D FEA. Their results showed that the critical load is more sensitive to the bearing width and the individual rubber layer thickness than it is to the number of rubber layers. Weisman and Warn [33] used experimental testing and FEA to investigate the critical load capacity of an elastomeric bearing and a lead-rubber bearing with shape factor values of 10 and 12, respectively. The results of this investigation showed that the lead core does not have a significant effect on the critical load over the 150–280 percent range of shear strain in comparison with elastomeric bearings without a lead core. Montuori et al. [34] studied the effect of the second shape factor on the stability of elastomeric bearings, confirming that the second shape factor significantly affects the stability of the bearing. Nguyen and Tassoulas [35] modeled a square and a rectangular unbonded steel-reinforced elastomeric bridge bearing in 3D under compression and shear in various lateral directions. A constitutive model based on the Yeoh strain energy density function was used to represent the behavior of the rubber. Their results showed that there was no significant effect of the shear direction on the stiffness at 50 percent shear displacement.

Mordini and Strauss [36] carried out FEA to study the vertical and horizontal behavior of fiber-reinforced rubber bearings, with the rubber modeled using Neo-Hookean and Ogden hyperelastic material models. Toopchi-Nezhad et al. [37] compared the behaviour of fiber-reinforced elastomeric isolators (FREIs) in unbonded and bonded applications. Osgooei et al. [38] used 3D FEA to study the behavior of circular fiber-reinforced elastomeric bearings under compression. In another study, Osgooei et al. [39] investigated the lateral response of unbonded rectangular FREIs when loaded in different directions. The behavior of unbonded FREIs that feature geometric modifications was investigated under pure compression [40] and combined compression and shear in [41]. Al-Anany and Tait [42] modeled bonded and unbonded FREI to study the effect of rotation on the vertical behavior of FREIs. Their results showed that Unbonded FREIs in comparison with Bonded FREIs experience lower normal stresses and shear strains in the elastomer. Osgooei et al. [43] investigated the variation in vertical stiffness of strip FREIs under lateral loading. Their results revealed that for bonded FREIs, the vertical stiffness decreases monotonically with increase of lateral displacement; while, for unbonded FREIs, the vertical stiffness decreases up to a particular shear deformation and then it increases. A FEA investigation on the compression of unbonded rubber pads including contact slip at the supports can be found in [44].

This paper presents the results of a study investigating the effect of rotation on the horizontal behavior of steel-reinforced elastomeric bearings. For these bearings, depending on the structural application, the rotation may be constant or vary while the bearing is sheared. This is the first systematic FEA study on the behavior of bearings under combined compression, lateral displacement and support rotation. As such, the discussion is limited to the simpler case of constant rotation. First, a 3D finite element model of a circular elastomeric bearing is developed in ABAQUS