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Three-dimensional finite element analysis of circular fiber-reinforced elastomeric bearings under compression

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ABSTRACT

Fiber reinforced elastomeric isolators (FREIs) are a relatively new type of elastomeric bearing. FREIs utilize fiber material for the reinforcing layers instead of steel which is used in conventional steel reinforced elastomeric isolators (SREIs). Unlike SREIs, where the steel reinforcing material is usually assumed to be rigid in extension, the reinforcing fiber layers are considered to be flexible in extension. As a result, the vertical response characteristics of FREIs differ from those of SREIs. In this study, a 3D parametric numerical finite element analysis (FEA) is carried out on sixteen circular FREI bearings. All bearings investigated have the same overall dimensions, while the thickness of elastomer layers and the axial stiffness of reinforcement are the parameters that are varied. FEA results, in terms of deformed shape, stiffness, stress and/or strain in reinforcing and elastomer layers are compared with predicted values obtained using the pressure solution and the pressure approach methods. Good overall agreement was observed between the FEA results and the results obtained from analytical solutions. It was concluded that the end boundary effect, which is often neglected, becomes a contributing factor on the vertical response for bearings reinforced with flexible reinforcements, or bearings with low shape factor values.

1. Introduction

Seismic isolation in North America is primarily limited to high importance or post-disaster buildings, such as historical structures, hospitals and emergency centers. This limitation is largely due to the high manufacturing and installation costs associated with traditional seismic isolation systems. Currently, it is not economically feasible to employ these traditional seismic isolation systems in smaller structures such as residential buildings. A reduction in both the weight and cost of isolators is expected to significantly increase the application of this valuable technology to ordinary low-rise buildings [1]. In steel reinforced elastomeric isolators (SREIs), which are the most common isolators in use, the overall weight is mainly due to the thick top and bottom steel end plates as well as the steel reinforcing shims. The high cost of SREIs is predominantly associated with the highly labor-intensive manufacturing process [2].

The role of the reinforcing layers in elastomeric bearings is to limit the lateral bulging of the elastomer under vertical compression loads, thus increasing the vertical stiffness of the bearings and suppressing the rocking mode of vibration [3]. Reinforcing layers also allow the elastomer to shear freely under lateral loads in order to maintain the large lateral flexibility requirement. The weight of SREIs can be reduced by eliminating the thick steel end plates and replacing the steel shims with reinforcement made of alternative materials having the same order of elastic stiffness, e.g. carbon fiber material [4]. These modifications alter the deformation pattern of a bearing under horizontal displacement. However, if properly designed these modifications can result in stable unbonded isolators having favorable seismic isolation characteristics [5,6].

Fiber reinforced elastomeric isolators (FREIs) are a relatively new type of elastomeric bearing that utilize fiber material for the reinforcing layers. Previous studies [2,4–7] have shown that it is possible to achieve adequate vertical stiffness with FREIs. Under horizontal cyclic testing, unbonded FREIs exhibit superior energy dissipation compared to bonded SREIs [6,7] resulting in improved seismic mitigation efficiency in terms of reducing base shear and isolator displacement [8,9]. In conventional SREIs, the reinforcing material is steel and is usually assumed to be rigid in extension. In FREIs however, the reinforcing fiber layers are flexible in extension, and thus the vertical response characteristics of FREIs may differ from those of SREIs.

Several analytical solutions have been developed to evaluate the vertical response of elastomeric bearings. One of the earliest analysis of the compression stiffness was conducted by Rocard [10] using an energy approach. Additional advancements were made by Gent and Lindley [11], who derived expressions for the compressive stiffness of incompressible infinite-strip-shaped and

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circular-shaped elastic layers bonded to rigid plates. Gent and Meinecke [12] subsequently extended the analysis and derived the compression modulus for square shape elastic layers. Lindley [13] applied the energy method to compressible elastic layers. Kelly [14] introduced the *pressure solution* (PS) method for determining the vertical compression stiffness of compressible elastic layers bonded to rigid plates. This method is based on the following three assumptions:

(i) The top and bottom surfaces of the elastomer layers remain horizontal after application of the vertical load.
(ii) Points on a vertical line in the initial state form a parabola after loading.
(iii) The normal stresses in the elastomer can be approximated by the pressure.

Tsai and Kelly [1,15,16] extended the PS method for analyzing the compression and bending stiffness of infinite-strip, rectangular and circular elastic layers bonded to flexible plates. Kelly [2] derived the compression stiffness of infinite-strip elastic layers bonded to flexible plates considering bulk compressibility. Kelly and Calabrese [17] derived the compression stiffness of incompressible rectangular and compressible circular pads bonded to flexible plates.

Tsai and Lee [18] derived the compression stiffness of infinite-strip, circular and square elastic compressible pads using a method similar to the PS, but relying only on the two kinematic assumptions (i and ii). This method hereafter is referred to as the *pressure approach* (PA). Tsai [19,20] used the PA method to derive the vertical stiffness of infinite-strip and circular bearings with flexible reinforcements considering the compressibility of the elastomer. Solutions were presented for the effective compression modulus for two boundary conditions (rigid-end and free-end), as well as the monotonic deformation case, where every layer in the bearing is assumed to deform identically, and thus has the same compression modulus.

Pinarbasi et al. [21,22] developed an analytical solution based on the modified Galerkin method for the analysis of elastic layers bonded to rigid plates for infinite-strip, circular and annular shapes. The order of the theory is based on the number of shape functions considered in the displacement expansions. The method was extended [23,24] to investigate the vertical response of elastic layers bonded to flexible plates.

A number of finite element analysis (FEA) studies investigating the response behavior of FREIs have been conducted and presented in the literature. Most of these studies have focused on the horizontal response characteristics of the bearings [25–29]. However, relatively few FEA studies have focused on the vertical response characteristics of FREIs. Toopchi-Nezhad et al. [30] carried out a 2D FEA to investigate the stress distribution and vertical stiffness of a strip FREI. Five different values of tensile stiffness were considered for the reinforcing material and the results were compared with predictions obtained using the PS method. It was found that for bearings with fiber reinforcement of relatively low stiffness, the FEA results significantly differ from the pressure solution based predicted values. Toopchi-Nezhad et al. [29] extended the 2D FEA and investigated the influence of individual elastomer layers on the vertical and horizontal response of unbonded strip FREIs. Kelly and Calabrese [17] performed FEA and investigated the vertical and horizontal response characteristics of strip, circular and square FREI bearings. 2D analysis on six strip FREI bearings was conducted under pure compression and combined compression and shear loads. The vertical response of six circular and six square FREI bearings was investigated using 3D FEA. The vertical stiffness values obtained from FEA were compared with predicted values obtained from the pressure solution method and good overall agreement was found.

This paper presents the results of a 3D parametric FEA of circular FREIs under compression. While the symmetry of the problem makes it possible to use axisymmetric 2D analysis, full 3D analysis is conducted so as to validate 3D FEA models against both the PS and PA analytical solutions. 3D finite element models such as these can subsequently be used to study the behavior of circular bearings under non-symmetric loading conditions, e.g., combined vertical and lateral loading, for which an axisymmetric analysis is not possible. To investigate the effect of reinforcement stiffness on the vertical response behavior of circular bearings with different shape factors (defined as the ratio of the total loaded area of one elastomer layer to the load free area), sixteen circular bearings with the same overall dimensions, but varying number of elastomer layers and a wide range of reinforcement tensile stiffness are modeled and analyzed using the commercially available finite element program MSC Marc [31]. In addition, this study also examines the effect of end boundary conditions as well as the magnitude of the vertical load on the overall response of the bearings. It should be noted that the analytical solutions are based on small deformation theory assuming linearly elastic material behavior, while the FEA incorporates a large deformation formulation, and the rubber is treated as a compressible Neo-Hookean hyperelastic material.

2. Review of analytical solutions

Among the various analytical solutions discussed earlier, the *pressure solution* (PS) and the *pressure approach* (PA) methods are used in this study. The PS methods is the most common method for calculating the vertical stiffness of elastomeric bearings and the PA method, although similar to PS, considers different end boundary conditions.

2.1. Pressure solution (PS)

Fig. 1 shows a circular elastic pad of radius b and thickness t bonded on top and bottom to flexible reinforcement plates of thickness t_f. Following the pressure solution, Kelly and Calabrese [17] derived the effective compression modulus E_c^{PS} of the circular fiber reinforced elastomeric pad considering the compressibility of the elastomer:

$$E_c^{PS} = 24GS^2(1+\nu_f)\frac{I_0(\eta) - \frac{2}{\eta}I_1(\eta)}{\alpha^2\left[I_0(\eta) - \frac{1-\nu_f}{\eta}I_1(\eta)\right] + \beta^2\frac{1+\nu_f}{2}I_0(\eta)} \tag{1}$$

where G is the shear modulus of the elastomer, $S = b/2t$ is the shape factor, ν_f is Poisson's ratio for the reinforcement material and I_i is

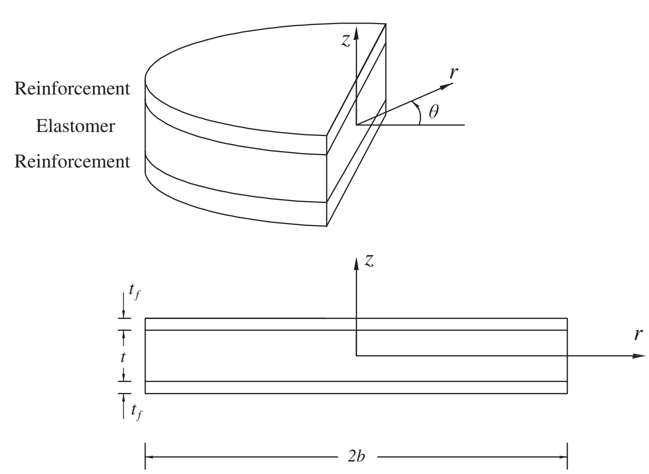

Fig. 1. A circular elastomeric pad bonded to flexible reinforcements.