Engineering Structures 150 (2017) 996–1012

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Simple mechanical models for the horizontal behavior of elastomeric bearings including the effect of support rotation

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A R T I C L E I N F O

Article history:
Received 14 March 2017
Revised 15 July 2017
Accepted 25 July 2017

Keywords:
Rubber bearings
Seismic isolation
Support rotation
Combined loading
Mechanical model

A B S T R A C T

Past studies have shown that the lateral behavior of a laminated elastomeric bearing is affected by axial load, and various mechanical models that consider the effect of horizontal–vertical coupling have been proposed. Those studies have characterized the effect of vertical load on the lateral stiffness and the lateral stability limit under the assumption that the bearing's top and bottom supports displace horizontally and vertically *only*, i.e., the supports do not rotate. In this study, the zero-rotation constraint is released, and the performance of different mechanical models in capturing the effect of support rotation on the lateral behavior of elastomeric bearings is evaluated. Three existing models are considered: the Nagarajaiah-Ferrell, Iizuka, and Han-Warn models. First, these three models are evaluated by comparing their predictions with results of Finite Element Analysis (FEA), assuming no rotation at the supports. The models are subsequently modified to incorporate support rotation. The modified models are evaluated using results from FEA under prescribed rotation values. In order to investigate the effect of bearing aspect ratio on the results, bearings with different second shape factors (2, 4 and 6) are considered. The results show that the modified models cannot accurately predict the lateral force at the instability (critical) point (defined as the displacement at which the tangent stiffness becomes zero). Depending on the axial load and rotation value, the modified models underestimate or overestimate the lateral force at the critical point. Nevertheless they predict the critical displacement with acceptable accuracy. It was found that in general the modified Han-Warn and modified Iizuka models provide more accurate predictions than the modified Nagarajaiah-Ferrell model. To improve upon these modified models, this paper proposes a new model capable of capturing the effect of rotation on the lateral response. This model is used to estimate the lateral stability limit and the results are compared against those from FEA. It is shown that the model can predict the lateral behavior of elastomeric bearings more accurately than the modified models.

1. Introduction

Seismic isolation using elastomeric bearings is an effective and widely used earthquake protection technique. In buildings, traditional practice places the isolation system at the foundation level and calls for the construction of rigid diaphragms above and below. The flexural rigidity of these diaphragms constrains the isolators from experiencing rotations. Recently, creative isolation designs have been introduced that reduce or eliminate these costly rigid diaphragms and in some cases move the isolation level higher up the structure. Another growing application of isolation is high-rise buildings, especially in Japan. Ohsaki et al. [1], who used FEA to study the performance of a 10-story isolated reinforced-concrete structure, noted that, aside from vertical and relative lateral displacements, the isolators experienced rotations at their supports.

When an elastomeric bearing is subjected to a large lateral displacement, the full axial load is carried through by the overlapping region between the top and bottom surfaces [2]. As the overlapping area decreases with increasing lateral displacement, there is a concern with the stability of the bearing. The combination of axial load and horizontal displacement affects the bearing's stability limit. Previous studies introduced mechanical models [3–13] to examine the stability of elastomeric bearings under the assumption that the bearing only sheared horizontally and only displaced vertically, while the supports did not rotate. The increasing use of elastomeric bearings in high-rise buildings, mid-story or column-top isolation applications, as well as in bridge applications, where bearings are expected to experience rotations, calls for an improved

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http://dx.doi.org/10.1016/j.engstruct.2017.07.079
0141-0296/

understanding and characterization of the behavior of elastomeric bearings under combined loading that includes rotation. In tall buildings, increased moment demands at the base of columns can result in bearing support rotations [1]. In mid-story or column-top isolation applications where columns are flexible, the bearing support connecting to the flexible column can experience rotation [14]. Finally, elastomeric bearings may also experience support rotations due to imperfections in construction [15].

Recent studies investigated the effect of rotation on the lateral behavior of bearings experimentally or numerically. Crowder and Becker [14] experimentally studied column-top isolation in a retrofit application and showed that, in the case of flexible columns, the end plate rotation due to the column's flexibility causes appreciable reduction in the lateral stiffness of the bearing. Ishii et al. [16] extended the previous model by Yamamoto et al. [8] to account for the effect of rotation on the horizontal behavior of elastomeric bearings. It was shown that end rotations do not affect the critical displacement. Using 3D FEA, Rastgoo Moghadam and Konstantinidis [17] confirmed that rotation does not significantly affect the critical displacement but noted that rotation can decrease or increase the critical shear force, depending on the rotation direction. It was concluded that imposing rotation at the supports, depending on the rotation value and axial force, can appreciably influence the lateral behavior of a rubber bearing. Another FEA study by Kalfas et al. [18] showed that when a bearing is subjected to axial and horizontal load and the end plate is allowed to rotate, the development of local tensile stresses changes the stiffness and damping ratio.

Various studies on the stability of laminated elastomeric bearings, assuming no rotation of the top/bottom supports, involved quasi-static and dynamic tests of bearings with different shape factors (defined for a single rubber layer as the ratio of loaded area to force-free area), second shape factors (defined for a bearing as the ratio of diameter, or width, to total thickness of rubber), geometric shapes, and rubber materials [10,19–26]. Some of the salient conclusions of these experimental studies are:

1. The axial load capacity decreases when the bearing is displaced laterally [10,20–26].
2. The lateral stiffness of the bearing decreases with increasing axial load [10,20–26].
3. In lead-core bearings, the lead core does not have a significant effect on the critical capacity when the bearing is laterally deformed [25].
4. The method recommended by code (known as the overlapping area method) to estimate critical capacity is overly conservative [23–26], especially for slender bearings when the horizontal displacement is equal to the bearing diameter/width [23,25].
5. Quasi-static and dynamic test results agree, confirming that quasi-static tests can reliably determine the instability of elastomeric bearings [26].
6. Dynamic tests revealed that bearings can still sustain loads beyond the static critical load without problems in the superstructure [10,26], but this conclusion is based on a limited number of tests [10]. It should be noted that most of design codes for elastomeric bearings do not allow the bearing to experience lateral displacements beyond the critical point.

The use of FEA to study the stability of rubber bearings has become increasingly popular over the past few years. The first study on the subject using FEA was conducted by Simo and Kelly [27]. The study used two-dimensional constitutive equations together with two-dimensional finite elasticity, extended to large displacements of the constitutive equations for an isotropic solid. A parametric study by Warn and Weisman [28] on the effect of geometry on the critical load of rubber bearings using 2D FEA showed that the bearing width and the individual rubber layer thickness are more important parameters than the number of rubber layers. Weisman and Warn [25] showed that the axial load capacity of an elastomeric bearing is not affected by the presence of a lead core in the bearing. Montuori et al. [29] studied the effect of the second shape factor on the stability of elastomeric bearings. They observed that for bearings with second shape factors ranging from 1.5 to 6.2 the lateral behavior and stability of the bearings are related to the value of second shape factor. A FEA investigation on the compression of unbonded rubber pads including contact slip at the supports can be found in [30].

While finite element models are indispensable for developing a good understanding of the behavior of elastomeric bearings, both at the global and local level, they are computationally much costlier and less practical than simple mechanical models. For this purpose, this study focuses on mechanical models capable of describing the lateral-vertical coupling and predicting instability in elastomeric bearings. The first two-spring simple mechanical model was proposed by Koh and Kelly [3], who used experimental results for natural rubber bearings to confirm that the model's accuracy. This model was improved by Koo et al. [4] by using an instantaneous apparent shear modulus instead of a constant shear modulus value. In this model, the shear modulus is a function of the shear strain and can be represented by a polynomial equation obtained by least-squares fitting of test results. The advantage of this modification is the elimination of imprecision associated with the constant shear modulus. Nagarajaiah and Ferrell [5] developed a nonlinear analytical model by extending the Koh-Kelly model to include large displacements. It was shown that this model is capable of predicting the instability point and that the critical load decreases with increasing lateral displacement. Iizuka [6] used the configuration of the Koh-Kelly model, but the formulation was expanded by introducing finite deformation and nonlinear springs. The parameters of the nonlinear rotational and shear springs in the model are determined through experimental testing. Unlike previous models, the advantage of this model is that it can easily handle a variable axial force. Han and Warn [7] proposed a 2D model consisting of a series of vertical springs with a simple bilinear constitutive relationship along with a shear spring. The solution process to find the critical point in the Han-Warn model is similar to the Iizuka model. In recent years, three-dimensional mechanical models have been proposed [8,9,16]. Although, based on comparison with experimental tests, these models are capable of predicting the lateral behavior of elastomeric bearings accurately, their complexity makes them difficult to use in practical applications.

Dynamic tests conducted by Vemuru et al. [10] showed that the stiffness of the bearings beyond the stability limit is larger than that predicted by quasi-static tests. As the Nagarajaiah-Ferrell model is based on quasi-static tests, the model cannot accurately predict the stiffness degradation beyond the stability point. Based on this observation, Vemuru et al. [10] proposed a new model by including higher order displacement terms in the stiffness of the rotational spring. The model is capable of characterizing the dynamic behavior of bearings more accurately than previous models, particularly beyond the instability point. In another study conducted by Vemuru et al. [11], vertical springs are introduced in the Nagarajaiah-Ferrell model to capture the vertical behavior of the bearings more accurately than in previous models. This model represents the coupled behavior of the bearing as a combination of reduction in vertical stiffness beyond the instability point and an increase in vertical displacement.

Forcellini and Kelly [12] modified the Koh-Kelly model to capture the tension buckling behavior of bearings. It was shown that the behavior of elastomeric bearings in tension is the 'mirror image' of those in compression. However, numerical and