Journal of Sound and Vibration 427 (2018) 1–14

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

An analytical model for predicting the lateral-torsion coupling property of laminated rubber bearings

Fangyuan Zhou [a], Zixiang Zhang [b], Dongdong Wu [a], Hongping Zhu [a,*]

[a] *School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan, Hubei, PR China*
[b] *CCCC Second Highway Consultants Co.,Ltd., Wuhan, Hubei, PR China*

ARTICLE INFO

Article history:
Received 20 February 2018
Received in revised form 9 April 2018
Accepted 11 April 2018
Available online 27 April 2018
Handling Editor: Erasmo Carrera

Keywords:
Laminated rubber bearing
Lateral-torsion coupling
Three-dimensional
Numerical model
Nonlinear analysis

ABSTRACT

Existing models for laminated rubber bearings neglect the lateral-torsion coupling property of their response behavior. Thus, in this paper, an analytical model considering the lateral-torsion coupling of laminated rubber bearings is proposed. The lateral stiffness and torsional stiffness of the bearing are determined by a three-dimensional multiple-parallel-spring model installed at the mid-height of the global analytical model. For numerical implementation, the bearing forces are found by solving the nonlinear equilibrium and kinematic equations using Newton's method, and the instantaneous stiffness matrix of the bearing is determined from the differentials of these equations. The response behavior of the model is confirmed by comparison with experimental data.

1. Introduction

Base isolation has been widely used to protect structures from the damaging effects of earthquakes [1–7]. Many of the isolated structures now in existence use laminated rubber bearings as the primary isolation devices. The dynamic characteristics of the laminated rubber bearing determine the response of the superstructure during seismic excitation. Thus, it is important to understand the mechanical properties of the laminated rubber bearing in advance.

As is well known, torsion adversely affects the response of both conventional structures and isolated structures. Lateral-torsional coupling in seismically isolated structures results from plan asymmetry in the superstructure and the isolation base. Indeed, because the equations of motion of the base and superstructure are coupled, any plan asymmetry in either subsystem creates lateral-torsional coupling in the combined isolated structure. Such coupling leads to an uneven displacement demand across the building plan, causing some isolators to experience larger deformations and forces than others. Because experience has shown that seismic isolation can be used in conjunction with asymmetric superstructures, the torsional response of asymmetric superstructures may subject the bearings to bi-directional lateral force and a torsional moment during seismic excitation. Thus, it is necessary to understand the mechanical properties of a laminated rubber bearing subjected to bi-directional lateral forces coupled with a torsional moment to precisely predict the dynamic response of the bearing.

Numerical models have been proposed to predict the dynamic properties of laminated rubber bearings in the past decades. Koh et al. [8] proposed a simple mechanical model to account for the dynamic properties of the bearing, considering

* Corresponding author.
E-mail addresses: fangyuanzhou@hust.edu.cn (F. Zhou), 549225836@qq.com (Z. Zhang), adam301@hust.edu.cn (D. Wu), hongpingzhu630@163.com (H. Zhu).

https://doi.org/10.1016/j.jsv.2018.04.018
0022-460X/

both shear and flexural deformations. However, the springs employed in the model are linear. To consider the nonlinear behavior of the bearing, semi-empirical bearing models for simulating the dynamic behavior of a laminated rubber bearing have been proposed [9–12]. The analytical model developed by Nagarajaiah and Ferrell [9] includes large displacements, large rotations, and nonlinearity in the rubber and can predict the unstable post-critical behavior of a laminated rubber bearing; the formulation of an analytical model, calibration, and verification using experimental results were conducted. Iizuka [10] proposed a macroscopic model for predicting the large-deformation behavior of laminated rubber bearings by introducing finite deformation and nonlinear springs into the Koh-Kelly model. Comparison with experimental testing results showed that the Iizuka model can accurately express characteristic large-deformation behaviors of laminated rubber bearings, such as hardening, load deterioration, and buckling phenomena, with simple calculations. Yamamoto et al. [11] and Kikuchi et al. [12] proposed an analytical model to predict the large-displacement response of seismically elastomeric bearings. The model is comprised of shear and axial springs and a series of axial springs at the top and bottom boundaries. For large shear deformations, elastomeric bearings exhibit stiffening behavior under low axial stress and buckling under high axial stress. The proposed model includes an interaction between shear and axial forces, nonlinear hysteresis, and a dependence on axial stress.

Han et al. [13,14] evaluated the capability of two analytical models to predict critical loads and displacements in elastomeric bearings by comparing the data from the model with the data from prior experimental studies. A global variance-based sensitivity analysis was performed on the analytical model exhibiting the best predictive capability to identify the model parameters to which the model prediction is most sensitive. Ryan et al. [15] developed a model that includes axial-load effects in a lead-rubber bearing by extending an existing linear two-spring model to include nonlinear behavior. The nonlinearity includes an empirical equation for the experimentally observed variation of yield strength. Lan et al. [16] used the transfer matrix method to analyze the mechanical behavior of a periodic bearing subjected to a compressive axial load and lateral shear deformation.

In addition to numerical mechanical models, finite-element (FE) models have been developed [17–20]. Osgooei et al. [17] investigated the vertical response properties of a bearing using three-dimensional FE analysis; they demonstrated good agreement among stress distributions obtained through FE analysis and analytical formulas. Mordini and Statuss [18] investigated the properties of a high damping rubber bearing; the Ogden model was used for static analysis, and a neo-Hookean model was used for dynamic analysis. Das et al. [19] performed a three-dimensional FE analysis of a bearing to investigate the effect of loading direction on the response to cyclic horizontal loads; the rubber material was represented by the Ogden model for hyper-elasticity and by the Prony series for viscoelasticity. Ohsaki et al. [20] conducted an FE analysis of a base isolated frame to investigate the deformation and stress distribution of rubber bearings under severe earthquake ground motion; horizontal seismic motions were applied to the base isolated frame, and the time histories of the interaction between the base and the rubber bearing as well as the complex local response of the isolator were investigated. Habieb et al. [21] performed a set of advanced finite element simulations on a small masonry prototype with frictional isolation. The simulation results were compared with the experimental data, indicating that the performance of friction-based isolation is considerably effective to isolate seismic-wave transmission into superstructure. Several accurate 3D FE analyses were carried out on a newly conceived low-cost fiber reinforced elastomeric isolator by Habieb et al. [22]. The numerical results showed an excellent isolation performance of the system, with a significant reduction of the inter-story drift.

In all of the aforementioned studies, the uni-lateral dynamic property of a laminated rubber bearing was investigated. However, in some engineering projects, the bearing is subjected to bi-directional lateral seismic excitation, and the laminated bearing may experience a torsional moment due to asymmetry of the superstructures. Thus, in this paper, an analytical model considering the lateral-torsion coupling of elastomeric seismic isolation bearings is proposed. The effect of a bi-lateral force and a torsional moment on the dynamic properties of laminated rubber bearings can be considered by the proposed model, and the accuracy of the proposed model is verified by comparison with experimental data.

2. Outline of the employed mechanical model

Fig. 1 shows the mechanical model postulated to represent the lateral-torsion coupling behavior of laminated rubber bearings. The model is comprised of a multiple-parallel-spring (MPS) plate at the mid-height, an axial spring along the vertical direction and a series of rotation springs at the bottom boundary. The MPS model proposed here is used to simulate the shear deformation and torsional deformation of the laminated rubber bearings during seismic excitation. Fig. 1 shows that the MPS model consists of a series of parallel-spring elements, where each parallel-spring element consists of a series of parallel springs attached to two rigid beams. It is assumed that rigid beam *B* has the same rotation angle as the lower plate and that rigid beam *A* has the same rotation angle as the upper plate. Thus, the parallel-spring element can simultaneously model the tension-compression deformation and the torsional deformation. The vertical and rotation properties of the bearings are simulated by a vertical spring and multiple rotation springs (MRS).

2.1. Basic equations

Fig. 2 shows the force and deformation conditions of the proposed model. From Fig. 2, the force-equilibrium conditions and the geometrical relationships of the deformations can be expressed as follows: