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An experimental study on unbonded circular fiber reinforced elastomeric bearings

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ABSTRACT

Seismic base isolation by introducing a flexible horizontal layer at the foundation level of a structure has proven to reduce the seismic demand. Steel reinforced elastomeric bearings have been used for that purpose extensively in the last years. More recently, innovative fiber reinforced elastomeric devices have been investigated as they bring important advantages as reduction of manufacturing and transport costs. The current article analyzes relevant mechanical properties for seismic isolation such as vertical and horizontal stiffness as well as damping capacity in fiber reinforced elastomeric bearings, focusing on the effect of shape geometry and material of the fiber reinforcement layers. Quasi-static cyclic experiments under vertical and combined horizontal and vertical load have been performed in order to investigate the effect of compression, horizontal deflection, frequency of the load and geometrical parameters. Compressive loads up to 12 MPa have been investigated. Moreover, the performance of bearings with round and square plan geometry under multidirectional loading is examined. Comparisons between the obtained results and data from previous works are discussed.

1. Introduction

Seismic isolation by introducing a flexible layer between the foundation and superstructure has proven to reduce the seismic demand, increasing the fundamental period [1]. Steel reinforced elastomeric bearings (SREBs) acting as seismic isolators have been extensively used in structural applications. In the last years diverse investigations performed on fiber reinforced elastomeric bearings (FREBs) have shown manufacturing and mechanical characteristics that bring important advantages with respect to SREBs [2–6]. The substitution of steel shims for glass or carbon fiber as reinforcement allows a substantial reduction on the weight of the system, while maintaining comparable tensile properties of the reinforcement layers and thus vertical behavior of the isolator. FREBs present also less geometrical constraints as they can be cut to any desired plan geometry from large sheets using standard techniques. Moreover FREBs can be located freely between foundation and structure, thus enabling the possibility to remove thick steel plates used to fix the isolator. The unfixed FREBs under lateral displacements present a unique rollover behavior allowed by the lack of flexural rigidity of the reinforcement, as the horizontal surfaces detach from the upper and lower supports, what causes a reduction on the lateral stiffness of the bearing. Full rollover is achieved when the vertical faces contact the supports, setting a limit for further rollover and increasing the overall stiffness of the bearing. Recently new application fields, besides the isolation of low rise buildings have been investigated. Fiber reinforced bearings for bridge seismic isolation [7], retrofitting of masonry buildings [8] or vibration isolation [9] have been analyzed with satisfactory results. The performance of FREBs as seismic isolation devices has been also tested using shake table experiments [10] and approximate models have been developed for the analysis of isolated structures under seismic excitation [11,12]. Important parameters for the performance assessment of elastomeric bearings are the vertical and shear stiffness as well as the damping capacity. European standards [13,14], provide very coarse assumptions for those parameters and do not consider other reinforcement material than steel. Experimental investigations on the compressive and lateral response of FREBs with rectangular and square shape have been previously performed [5,6,15–20] but fiber reinforced bearings with circular plan geometry in unfixed application are little investigated. The reinforcement layers used in most of the available studies consist of carbon fiber fabric. Glass fiber as reinforcement for unfixed elastomeric bearings has been addressed sparsely. Moreover, very few of the published works on fiber reinforced bearings investigate the effect of compression loads up to 12 MPa combined with horizontal deformation. The objective of this work is to describe both the vertical and horizontal mechanical behavior of fiber reinforced elastomeric bearings, focusing on the influence

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of circular shape, under high compressive and combined loads, analyzing the effect of geometry, compression, frequency of load, horizontal strain and material of the reinforcement. Quasi-static experiments were performed to determine the vertical and horizontal stiffness and damping capacity of unfixed elastomeric bearings with circular and rectangular shape under different horizontal load directions. Moreover, analytical results obtained from the literature are compared with the experimental results.

2. State of the art review

2.1. Vertical behavior

Previous studies have analyzed the feasibility of fiber reinforced elastomeric bearings. [3] demonstrated experimentally that steel shims could be substituted by different fiber types, obtaining higher vertical stiffness and effective damping than conventional SREBs. [16] performed experiments on carbon FREBs obtaining acceptable values for vertical stiffness and frequency. Larger stiffness values were found in specimens with larger aspect ratio (width to total height ratio). [17] tested the compressive response of square FREBs and SREBs made from recycled rubber. It was proven that carbon fiber reinforced bearings performed better than glass fiber and steel reinforced devices, with vertical stiffness increasing with the applied load. Several close form solution methods have been developed to determine the compressive stiffness of elastomeric bearings. Expressions for incompressible rubber and rigid reinforcement were developed by [21,22]. [23] derived the *pressure solution* method that is based on the approximation of normal stresses by the pressure and two kinematic assumptions (top and bottom surfaces of elastomer remain horizontal and points on a vertical line form a parabola after loading). This method takes into account the compressibility of the elastomer and flexibility of the reinforcement. Based on this method [24] developed simplified, design code oriented formulations for infinite strip, circular, square, and annular pad geometries. Using only the two mentioned kinematic assumptions, [25] developed expressions for the effective compression modulus of circular bearings under rigid-end and free-end boundary conditions accounting for compressibility of the elastomer and flexibility of reinforcement layer, respectively. The solution for the compression modulus of a compressible circular bearing with flexible reinforcements considering free ends derived by [25] is:

$$E_c = \frac{n}{\frac{2}{E_c^{(1)}} + \frac{n-2}{(E_c)_{mono}}} \tag{1}$$

where $E_c^{(1)}$ is the compression modulus for an external rubber pad bonded to a flexible reinforcement layer given by the Eq. (2) and $(E_c)_{mono}$ is the compression modulus for an internal rubber pad bonded to flexible reinforcement layers calculated using Eq. (3).

$$E_c^{(1)} = 2\mu + \frac{\mu\lambda}{\lambda+\mu} + \frac{\lambda^2(\lambda+2\mu)}{(\lambda+\mu)^2}\left(\frac{\alpha_0^2}{2D_2}\right)\left[I_0(\beta_1 b) - \frac{2I_1(\beta_1 b)}{\beta_1 b}\right] \tag{2}$$

$$(E_c)_{mono} = 2\mu + \frac{\mu\lambda}{\lambda+\mu} + \frac{\lambda^2(\lambda+2\mu)}{(\lambda+\mu)^2}\left(\frac{\alpha_0^2}{2D_1}\right)\left[I_0(\beta_0 b) - \frac{2I_1(\beta_0 b)}{\beta_0 b}\right] \tag{3}$$

where b is the radius of the bearing, t is the thickness of the rubber layer, E_f, ν_f and t_f are the elastic modulus, Poisson's ratio and thickness of the reinforcement, μ and λ are Lame's constants, I_i is the modified Bessel function of the first kind of order i and α_0, α_1, β_0, β_1, D_1, and D_2 are given by Eqs. (4)–(7), respectively.

$$\alpha_0 = \frac{1}{t}\sqrt{\frac{12\mu}{\lambda+2\mu}} \qquad \alpha_1 = \sqrt{\frac{12\mu(1-\nu_f^2)}{E_f t_f t}} \tag{4}$$

$$\beta_0 = \sqrt{\alpha_0^2 + \alpha_1^2} \qquad \beta_1 = \sqrt{\alpha_0^2 + 0.75\alpha_1^2} \tag{5}$$

$$D_1 = \frac{\alpha_0^2}{\lambda+\mu}\left[\left(\frac{\lambda}{2}+\mu\right)I_0(\beta_0 b) - \mu\frac{I_1(\beta_0 b)}{\beta_0 b}\right] + \frac{\alpha_1^2}{1+\nu_f}\left[I_0(\beta_0 b) - (1-\nu_f)\frac{I_1(\beta_0 b)}{\beta_0 b}\right] \tag{6}$$

$$D_2 = \frac{\alpha_0^2}{\lambda+\mu}\left[\left(\frac{\lambda}{2}+\mu\right)I_0(\beta_1 b) - \mu\frac{I_1(\beta_1 b)}{\beta_1 b}\right] + \frac{0.75\alpha_1^2}{1+\nu_f}\left[I_0(\beta_1 b) - (1-\nu_f)\frac{I_1(\beta_1 b)}{\beta_1 b}\right] \tag{7}$$

The vertical stiffness can be calculated as:

$$k_v = \frac{E_c A}{t_r} \tag{8}$$

where A is the loaded area of the bearing and t_r is the total thickness of elastomer layers.

2.2. Horizontal behavior

According to current European standards [13,14], the horizontal stiffness of reinforced elastomeric bearings can be determined based on the value of a shear modulus, G that is assumed constant and dependent on material and ambient conditions. The theoretical value is given by the expression (9)

$$K_h = \frac{GA}{t_r} \tag{9}$$

where G is the shear modulus of the elastomer.

Experimental investigations [4–6,16,26,27,15,28] indicate that the assumption of a constant shear modulus result in inaccurate estimations of the horizontal behavior of FREBs. A common characteristic obtained in previous studies is a remarkable decrease of horizontal stiffness due to rollover on the tested specimens, regardless of geometry, shape ratio and reinforcement mechanical properties. [5] proposed a closed form solution for the horizontal stiffness of square FREBs accounting for the nonlinear behavior of the materials and the influence of compressive stress:

$$K_{h,roll} = \frac{GA^2}{t_r}\left[1 - \left(\frac{p_z}{p_{crit,0}\left(1-\left(\frac{u_x}{A}\right)^u\right)}\right)^2\right]\left(1 - \frac{u_x}{A}\right) \tag{10}$$

where p_z is the vertical stress, $u = 2$, $p_{crit,0}$ is the critical load as defined by [14] and u_x is the horizontal deformation.

[15] proposed a simplified expression for the equivalent linear horizontal stiffness, (11).

$$K_{h,equiv} = \frac{GA_{c,ave}}{t_r} \tag{11}$$

where the area of contact between the bearing and the supports, A_c varies with the applied displacement, The average value $A_{c,ave}$, (12), used in (11) is the average between the contact area at displacement equal to zero ($d = 0$) and the contact area at the maximum displacement ($d = d_{max}$) reached by the bearing.

$$A_{c,ave} = \frac{A_c(d=0) + A_c(d=d_{max})}{2} \tag{12}$$

Regarding the damping behavior, European standards recommend cyclic shear loading tests to determine the value, as no analytical formulation is given. [14] presents the following expression to calculate the equivalent damping coefficient, ξ from experimental data.

$$\xi = \frac{2W}{\pi K_h (u_x^+ - u_x^-)^2} \tag{13}$$