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Critical load of slender elastomeric seismic isolators: An experimental perspective

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ABSTRACT

One of the most important aspects of the seismic response of elastomeric isolators is their stability under large shear strains. The bearing capacity of elastomeric isolators, indeed, progressively degrades while increasing horizontal displacement. This may greatly influence the design of elastomeric isolators, especially in high seismicity regions, where slender elastomeric isolators subjected to large horizontal displacements are a common practice. In the current design approach the critical load is evaluated based on the Haringx theory, modified to account for large shear strains by approximate correction factors.

In this paper the critical behavior of a pair of slender elastomeric devices is experimentally evaluated at different strain amplitudes, ranging from approximately 50% to 150%. The experimental results are then compared to the predictions of a number of semi-empirical and theoretical formulations.

The main conclusion of this study is that current design approaches are overly conservative for slender elastomeric seismic isolators, since they underestimate their critical load capacity at moderate-to-large shear strain amplitudes.

1. Introduction

An elastomeric isolation bearing consists of a number of rubber and steel layers mutually vulcanized, to provide high stiffness in the vertical direction together with large deformability in the horizontal direction. The elastomeric isolators work like a filter lengthening the fundamental period of vibration of the structure, thus reducing the seismic effects (interstory drifts, floor accelerations, stresses in the structural members, etc.) generated in the superstructure. However, this reduction is accompanied by large horizontal displacements in the isolators, which may significantly reduce their axial load capacity [1–4].

The earliest theoretical approach for the evaluation of the critical axial load of rubber bearings was introduced by Haringx [5], considering the mechanical characteristics of helical steel springs and rubber rods. Same assumptions have been made later by Gent [6] considering multilayered rubber compression springs. Basically, the Haringx's theory is based on a linear one-dimensional beam model with shear deformability, within the hypothesis of small displacements. The critical buckling load of elastomeric seismic isolators is expressed as:

$$P_{cr,0} = \frac{2 \cdot P_E}{1 + \sqrt{1 + 4\pi^2 \frac{(EI)_{eff}}{(GA_s)_{eff} \cdot L^2}}} \tag{1}$$

in which: $(GA_s)_{eff}$ and $(EI)_{eff}$ are the effective shear rigidity and effective flexural rigidity, respectively, of the elastomeric isolators, computed based on the bending modulus (E) and dynamic shear modulus (G_{dyn}) of rubber, moment of inertia of the bearing about the axis of bending (I) and bonded rubber area (A_s);

P_E is the Euler load for a standard elastic column:

$$P_E = \frac{\pi^2 \cdot (EI)_{eff}}{L^2} \tag{2}$$

L is the total height of rubber layers and steel plates excluding top and bottom connecting steel plates.

Various authors proposed different relations to evaluate the effective shear and flexural rigidity of laminated rubber bearings. In this paper, reference to the formula derived by Buckle and Kelly [1], Koh and Kelly [2] has been made:

$$(GA_s)_{eff} = G_{dyn} \cdot A_s \cdot \frac{L}{t_e} \tag{3}$$

$$(EI)_{eff} = E_r I \cdot \frac{L}{t_e} \tag{4}$$

where t_e is the total thickness of the rubber layers and E_r is the elastic modulus of the rubber bearing evaluated based on the primary shape factor S_1 and rubber Young's modulus E_0 as:

$$E_r = E_0(1 + 0.742 \cdot S_1^2) \tag{5}$$

The primary shape factor S_1 is defined as the ratio between the loaded area of the bearing and the area free to bulge of the single rubber layer ($S_1 \approx D/4t_i$ for circular bearings, where D is the diameter

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of the isolator and t_i the thickness of a single rubber layer). The rubber Young's modulus E_0 is usually taken equal to 3.3 G_{dyn} to 4 G_{dyn}.

The Haringx's theory has been later applied by Naeim and Kelly [7], with a series of simplified assumptions, for commercial elastomeric seismic isolators. According to Naeim and Kelly [7], the critical buckling load of elastomeric seismic isolators can be expressed in terms of the primary and secondary shape factors S_1 and S_2, the latter being defined as the ratio between the maximum dimension of the cross section of the isolator and the total height of rubber. For circular elastomeric isolator, for instance, Naeim and Kelly [7] provides:

$$P_{cr,0} = \frac{\pi}{2\sqrt{2}} \cdot (GA_s)_{eff} \cdot S_1 \cdot S_2 \tag{6}$$

Subsequently, Kelly [8] derived a more refined formulation of the buckling load of elastomeric isolator:

$$P_{cr,0} = \frac{\pi}{2\sqrt{3}} \cdot (GA_s)_{eff} \cdot \sqrt{\frac{0.742 \cdot E_0}{G}} \cdot S_1 \cdot S_2 \tag{7}$$

The secondary shape factor S_2 is defined as the ratio between the bearing maximum dimension and the total thickness of all the rubber layers ($S_2 \approx D/t_e$ for circular bearings, where t_e is the total thickness of all the rubber layers). It is interesting to note that the critical buckling load capacity evaluated considering the expressions (6) and (7), differs by 10–20%, depending on the value (between 3.3G and 4G) assumed for the rubber Young's modulus.

Lanzo [9] modified the Haringx's expression by taking into account the axial stiffness of the rubber bearing $(EA)_{eff}$:

$$P_{cr,0} = \frac{2 \cdot P_E}{1 + \sqrt{1 + 4\pi^2 \left(-\frac{(EI)_{eff}}{(EA)_{eff} \cdot L^2} + \frac{(EI)_{eff}}{(GA_s)_{eff} \cdot L^2} \right)}} \tag{8}$$

where $(EA)_{eff}$ is the effective axial stiffness of the rubber bearing, evaluated as:

$$(EA)_{eff} = E_r \cdot A \cdot \frac{L}{t_e} \tag{9}$$

In Italy, the current design approach [10] refers to a formulation of the critical load similar to (but more conservative than) that initially proposed by Naeim and Kelly [7] (see Eq. (6)):

$$P_{cr,0} = G_{dyn} \cdot A_s \cdot S_1 \cdot S_2 \tag{10}$$

where G_{dyn} is the dynamic shear modulus derived from the qualification tests of the elastomeric isolator.

More recently, a less conservative variant of the Naeim and Kelly formulation has been adopted in the new European Standard EN11529 [11]:

$$P_{cr,0} = 1.3\ G_{dyn} \cdot A_s \cdot S_1 \cdot S_2 \tag{11}$$

For all the above mentioned formulations, the buckling load at the target shear displacement (u) is evaluated as a function of the ratio between the effective area of the inner shim plate (A) and the overlap area of the displaced bearing (A_r) (see Fig. 1):

$$P_{cr} = P_{cr,0} \cdot \frac{A_r}{A} \tag{12}$$

For circular bearings, for instance, the overlap area at the target displacement is given by:

$$A_r = (\varphi - \sin\varphi) \cdot \frac{D^2}{4} \tag{13}$$

with

$$\varphi = 2 \arccos\left(\frac{u}{D}\right) \tag{14}$$

Several experimental studies of the buckling behavior of elastomeric seismic isolators have been carried out in the past [12,1,3,4,13]. In this paper, the critical load of a couple of slender (low shape factors) elastomeric bearings is experimentally evaluated. Test set-up and experimental program are presented first in detail. Then, the experimental results are compared with the predictions of the theoretical formulations presented in the previous paragraph.

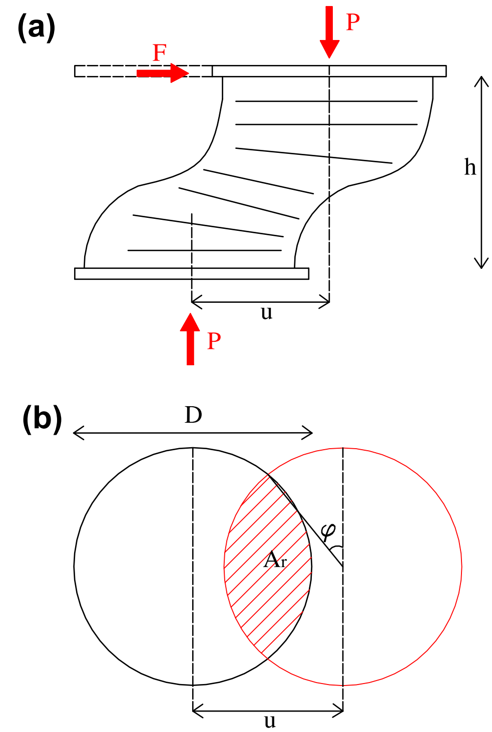

Fig. 1. (a) Schematic deformed shape of an elastomeric bearing subjected to shear and compression; (b) effective cross section area as a function of shear displacement.

2. Experimental tests

2.1. Test specimens

Test specimens are a couple of 1:2 scaled circular elastomeric bearings with 200 mm diameter and 10 rubber layers with 8 mm thickness. Bearing geometrical properties are summarized in Table 1.

The mechanical properties of the specimens have been derived from a number of standard cyclic tests, performed in accordance with the test procedure prescribed in the Italian seismic code [10] for the qualification of elastomeric bearings. The static shear modulus (G_{stat}), in particular, has been derived from a quasi-static test consisting of five cycles at 0.1 Hz frequency of loading and 100% shear strain amplitude. According to the NTC 2008 [10], G_{stat}

Table 1
Elastomeric bearings details.

Outer diameter	D_e (mm)	200
Inner diameter	D (mm)	180
Rubber layer thickness	t_i (mm)	8
Number of rubber layers	n_{ti}	10
Steel shim thickness	t_s (mm)	2
Number of steel shims	n_{ti}	9
Total height of rubber	t_e (mm)	80
Primary shape factor	S_1	5.63
Secondary shape factor	S_2	2.25