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Experimental investigation of cavitation in elastomeric seismic isolation bearings

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ABSTRACT

Design standards for seismic isolation of nuclear power plants in USA will consider the effects of beyond design basis loadings, including extreme earthquakes. Seismic isolation is being considered for new build nuclear power plant construction and design of isolation systems will have to consider these extreme loadings, which includes the possibility of net tensile force in bearings under beyond design basis shaking.

A series of experiments were conducted at University at Buffalo to characterize the behavior of elastomeric bearings in tension. Sixteen low damping rubber bearings from two manufacturers, with similar geometric properties but different shear moduli, were tested under various loading conditions to determine factors that affect cavitation in an elastomeric bearing. The effect of cavitation on the shear and axial properties of elastomeric bearings was investigated by performing post-cavitation tests. The test data were used to validate a phenomenological model of an elastomeric bearing in tension, which is implemented in OpenSees, ABAQUS and LS-DYNA.

1. Introduction

There are two types of elastomeric seismic isolation bearings being implemented in the United States at this time, namely, low damping rubber (LDR) and lead rubber (LR) bearings. The LDR and LR bearings utilize low damping natural rubber as the base compound. The LR bearing is a LDR with a central lead core, which provides energy dissipation. The response of these types of elastomeric bearings in tension is assumed to be identical because the lead core does not contribute to tensile strength and stiffness.

Tensile deformation in elastomeric bearings has traditionally been considered undesirable. Design codes and standards that explicitly acknowledge response in axial tension either do not allow tensile loading or limit the value of allowable tensile stress in elastomeric bearings under design-basis loading. The Japanese specifications for design of highway bridges [1] limit the tensile stress in G8 and G10 rubber (rubber classes with shear modulus of 0.8 and 1 MPa, respectively) to 2 MPa. Eurocode 8 restricts the use of elastomeric bearings if axial tensile force is expected during seismic loadings [2]. The Chinese seismic design code limits the tensile stress to 1 MPa [3].

Experiments have shown that elastomeric bearings may sustain large tensile strains up to 100%, following cavitation, without rupture [4]. The design codes and guidelines for seismic isolation of nuclear power plants in USA [5,6] consider the effects of beyond design basis earthquake loadings, which may produce net tensile force in one or more bearings. Similarly, the use of isolation for tall buildings may result in tensile loading for design basis and beyond design basis shaking. The tensile properties of elastomeric bearings need to be investigated to consider tensile loading in seismic isolator design, which would enable development of robust mathematical models to capture the load–deformation behavior in tension.

The response of an elastomeric bearing under tensile loading is characterized by the formation of cavities in the volume of the rubber. Gent and Lindley [7] explained that fracture inside a rubber layer occurs at a critical hydrostatic stress value, which is related to a critical value of applied tensile stress. This critical stress, known as the cavitation stress, depends mainly on the rubber compound.

Much of the initial work on cavitation of elastomers was done by Gent and Lindley [7]. They used bonded rubber cylinders in their experiments to investigate behavior under tensile loading. The tensile behavior of bonded rubber is highly dependent on thickness, or more appropriately the shape factor, *S*, which is defined as the bonded rubber area divided by the perimeter area free to bulge. Shape factors in the range from 10 to 30 are practical

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Table 1
Experimental work on the tensile properties of elastomeric bearings.

Reference	Bearing properties	Focus
Clark [10]	HDR, diameter 176 mm, shape factor ~20	Monotonic tensile failure
Iwabe et al. [4]	LDR, LR, HDR bearings, diameter 500 mm and 1000 mm, shape factor ~30	Tension, shear-tension, post-cavitation mechanical properties
Kato et al. [11]	LDR, diameter 500 mm and 1000 mm, varying bearing plate thickness, shape factor ~33	Tension, scale effect, bearing plate thickness
Shoji et al. [12]	LR, 240 × 240 mm, shape factor ~8	Cyclic deterioration under tension
Feng et al. [13]	LR, diameter 100 mm, shape factor ~15	Tension, mechanical properties, three-dimensional dynamic loading
Warn [14]	LDR, LR, outer diameter 152 mm, inner diameter 30 mm, shape factor ~12	Tension, coupling of horizontal and vertical motion
Constantinou et al. [15]	LDR, diameter 250 mm, shape factor ~9	Single cycle tensile loading

for seismic isolation of buildings, bridges and infrastructure. Unfortunately, there is little experimental data on the behavior of elastomeric bearings in tension with shape factors in this range. A summary of the relevant experimental work is presented in Table 1. Only work on seismic isolation bearings is identified in the table and studies on bonded rubber cylinders (e.g., [8,9]) are not described.

Figs. 1 and 2 present the behavior of LDR bearings in pure tension and in tension with co-existing shear, respectively.

Some of the important conclusions of these experimental studies were:

1. A substantial reduction of tensile stiffness occurs at a critical tensile stress (cavitation stress), which depends on the shear modulus and shape factor.
2. The load–deformation behavior in tension is linear up to cavitation with the tensile stiffness approximately equal to the compressive stiffness, followed by nonlinear post-cavitation behavior.
3. Tension coupled with shear loading increases the tensile load and deformation capacity of a bearing when compared to pure tension.
4. Under cyclic loading the tensile strength decreases, and the extent of the reduction is a function of the maximum tensile strain experienced in previous cycles.
5. The state of tension during shear loading has minimal effect on shear stiffness and shear hysteresis loops.

The behavior of elastomeric bearings under cyclic tensile loading is described in detail in Kumar et al. [16] and a phenomenological model was proposed to model such behavior. The model is validated using the data described in this paper, and included in models of elastomeric bearings now available in OpenSees [17], ABAQUS [18] and LS-DYNA [19].

2. Experimental plan

2.1. Model bearing properties

The geometric and material properties of the model bearings were based on considerations of (a) elastomers used in seismic isolation bearings, (b) commercially available rubber sheet thickness, (c) available molds for fabricating bearings, (d) axial load capacity of the Single Bearing Testing Machine (SBTM) at the University at Buffalo, and (e) bending moment capacity of the triaxial load cell in the SBTM. The physical limitations of the SBTM limited the diameter of the bearings to 300 mm and the total rubber thickness to approximately 150 mm, enabling the application of significant axial pressures and shearing strains. The target shape factors were 10 and 20.

Two manufacturers, Dynamic Isolation Systems, Inc. (DIS) and Mageba, each provided eight bearings for the experiments. The bonded diameter, shear modulus, and cover rubber thickness of the bearings differed by manufacturer; the DIS bearings had a central hole.[1] Each set of eight bearings had the same diameter, with two shape factors per set. The rubber layer thickness was either 7 mm (A) or 4 mm (B). The bearings were identified as DA1, DB1, MA1, MB1, etc., where the first letter refers to the manufacturer (D for DIS and M for Mageba), the second letter identifies the rubber layer thickness (or shape factor), and the number identifies the specific bearing. For example, bearing DA1 was manufactured by DIS with a rubber layer thickness 7 mm.

The effective shear modulus, G, of a bearing was determined experimentally at 100% shear strain, and was used to calculate the mechanical properties of a bearing. The shape factor, S, of the bearings with (DA and DB) and without (MA and MB) a central hole is calculated using:

$$S = \frac{D_o - D_i}{4t_r}: \text{ with central hole} \quad S = \frac{D_o}{4t_r}: \text{ without a central hole} \tag{1}$$

where D_o is the outer diameter excluding the cover thickness; D_i is the internal diameter; and t_r is the thickness of single rubber layer. The moment of inertia, I, and the compression modulus, E_c, is calculated as:

$$I = \frac{\pi}{64}\left[(D_o + t_c)^4 - D_i^4\right] \quad E_c = \left(\frac{1}{6GS^2F} + \frac{4}{3K}\right)^{-1} \tag{2}$$

where t_c is added to the outer diameter to include a contribution from half of the cover rubber thickness to the moment of inertia (this is a common assumption made for small size bearings to approximate the effect of the cover rubber); F is a factor to account for the central hole in a circular bearing [15]; and K is the bulk modulus of rubber, which is assumed to be 2000 MPa: the default value in seismic isolation specifications (e.g., [21,22]).[2]

The vertical stiffness in compression and in tension prior to cavitation, K_{v0}, and the horizontal stiffness, K_{H0}, are given by:

$$K_{v0} = \frac{AE_c}{T_r} \quad K_{H0} = \frac{GA}{T_r} \tag{3}$$

where A is the bonded rubber area of a bearing; and T_r is the total thickness of rubber layers in a bearing. The critical buckling load, P_{cr}, and the critical displacement, u_{cr}, in compression are:

$$P_{cr} = \sqrt{P_E G A_S} = \frac{\pi\sqrt{E_r G I A}}{T_r} \quad u_{cr} = \frac{P_{cr}}{K_{v0}} \tag{4}$$

where A_S is the shear area and E_r is the rotational modulus of a bearing. The cavitation force, F_c, and cavitation displacement, u_c, in tension are:

$$F_c = 3GA \quad u_c = \frac{F_c}{K_{v0}} \tag{5}$$

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[1] Results of tensile tests on elastomeric bearings with a central hole are likely better correlated to the behavior of LR bearing in tension than tests on bearings without a hole [20].

[2] Reported values of bulk modulus vary from 1000 MPa to 3500 MPa (e.g., [23–26]). The wide range is due to the different methods used to estimate the modulus and the errors in those experiments. The recent study of Kelly and Lai [26], which back-calculated the modulus from bearing tests, estimated $K = 2300$ MPa, which supported the use of 2000 MPa here.