Engineering Structures 56 (2013) 656–663

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Tension buckling in rubber bearings affected by cavitation

James M. Kelly [1], Maria Rosaria Marsico [2,*]

Department of Civil and Environmental Engineering, Earthquake Engineering Research Center, University of California, Berkeley, United Kingdom

ARTICLE INFO

Article history:
Received 23 March 2012
Revised 4 April 2013
Accepted 27 May 2013
Available online 2 July 2013

Keywords:
Base isolation
Rubber bearing
Cavitation damage
Compressibility
Bulk modulus
Tension buckling

ABSTRACT

Multilayer laminated rubber bearings are the most common antiseismic devices, typically used to isolate buildings. They are made with steel reinforcing layers that provide a vertical stiffness several hundred times the horizontal one. Although these bearings appear to be very stable, they face a buckling phenomenon, caused by low shear stiffness, that needs to be investigated.

In particular cases, seismic codes might require that bearings take some amount of tension that should be contemplated in the design. Several studies demonstrated that the buckling analysis for compression leads to the prediction that the isolator can buckle in tension at a load close to that for buckling in compression.

Moreover, the predicted tensile buckling load is in general, not achievable, since the elastomer in tension experiences cavitation at relatively low tension stresses. However, numerical simulations have shown that tensile buckling in multilayer elastomeric bearings is also possible in the absence of cavitation.

In this paper an analytical formulation to predict the instability of a rubber bearing affected by cavitation is elaborated. A procedure to calculate buckling load in tension in the presence of cavitation is developed for both long strip bearings and circular bearings. The analysis is conducted by using an analytical model that describes the effects of cavitation on both compressive and bending stiffness of rubber bearings used for antiseismic purposes.

1. Introduction

Many recent examples of isolated buildings use multilayer laminated rubber bearings with steel reinforcing layers as the load-carrying components of the structure [1–3]. The internal steel plates provide a vertical stiffness several hundred times the horizontal stiffness [4], therefore these bearings appear to be very stable. Nevertheless, the low shear stiffness causes a buckling phenomenon that has been widely studied and the developed theory is considered to be reasonably accurate to design bearings with a large safety factor against the buckling instability [5–7].

The buckling theory is based on a linear elastic analysis and, even though the elastomer is not really linearly elastic, the predominant deformation is one of shear. The elastomers typically used in bearings are very linear in shear over a large range of strain [8]. Studies conducted by Kelly and further researchers [9–11] have demonstrated that the linear theory, while approximated, is relatively accurate and is adequate for most design purposes.

Unexpectedly, the buckling analysis for compression predicts that the isolator can buckle in tension at a load close to that for buckling in compression. There are many examples of unusual systems that buckle in tension but effectively the tension forces are always transferred to compression elements that produce the instability. This is not the case that we want to study, where the buckling process is really tensile.

In order to elucidate the idea of compression and tension buckling in such bearings, an extremely simple linear elastic model has been developed. It might be argued that the tensile buckling may be an artefact of the model itself and not of the isolator. For this purpose, results of the simple model have been verified through numerical simulations [12,13], by using a finite element model of a multilayer elastomeric bearing. They show that the prediction of tensile buckling by using the simple linear elastic theory is in fact accurate and not an artefact of the model.

In the numerical simulations already developed the occurrence of cavitation is neglected [14–17]. Nevertheless, the predicted tensile buckling load will generally not be achievable in practice, since the elastomer in tension will experience cavitation at relatively low tension stresses.

Consider the cross section of a single layer of rubber in a multilayer elastomeric bearing, highly constrained by rigid steel plates on its upper and lower surfaces and under hydrostatic compressive and tensile loading. On the free edges, stress components in the

* Corresponding author. Tel.: +44 (0) 1392 723594.
E-mail address: m.r.marsico@exeter.ac.uk (M.R. Marsico).
[1] Pacific Earthquake Engineering Research Center, Richmond Field Station, University of California, Berkeley, 13JEST01 S. 46th Street, Richmond, CA 94804-4698, USA.
[2] Department of Mechanical Engineering, University of Bristol, Queens Building, University Walk, Bristol BS8 1TR, UK.

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.05.051

loading and the out-of-plane directions are generated, but the material is not constrained in the horizontal direction. On the other hand, in the centre the material is confined in all three directions and a positive or negative hydrostatic state of stress is developed [18]. Fig. 1 shows the state of tension stress in the central region of a layer of rubber, rigidly constrained.

Although bearings are typically used in compression, in the case of tall buildings in near-fault locations, seismic code requirements can lead to situations where some bearings in an isolation system can be required to take some amount of tension. Research has already been conducted on the simultaneous occurrence of tension and shear, since it allows the prevention of damage developing due to cavitation in the isolator [14].

Hereafter, the authors intend to study the tension buckling when cavitations occur. Cavitation damage starts to develop at the centre region where the largest hydrostatic tensile stress state exists [18]. Under this state of triaxial tension, the rubber, which is apparently intact, develops internal ruptures that can tear open and form cracks. Therefore, further increase of load causes the damaged region to expand [19].

It is not clear if bubbles in the rubber develop, but it has been shown experimentally that a large reduction in the bulk modulus can take place when cavitation happens. It is also likely that the shear modulus is unaffected by cavitation [18].

In most of the analyses on the deformation of the rubber, the material is treated as incompressible because of the high ratio of the initial bulk modulus to the shear modulus [19,20]. However, in the case of a rubber bearing, where the rubber is highly constrained, the assumption of incompressibility may not always be realistic.

The bulk modulus has values that depend on vulcanisation and temperature and it is generally assumed to be strain independent, with typical values between 2000 and 3000 MPa [21]. When cavitation happens, the bulk modulus reduces and, consequently, the ratio of the bulk modulus to the shear modulus is substantially reduced. Thus, the mechanical properties of the bearing, essential for the buckling analysis, such as the effective compression modulus and the bending stiffness, must include the effect of compressibility [22].

The approach that has been adopted to define the main mechanical properties consists of implementing a simplified theory based on two assumptions concerning the kinematics of the deformation and the stress state. The first one considers that, in the cross section, the points on a vertical line before deformation lie on a parabola after loading, and the second one presumes that the horizontal planes remain horizontal [23]. These assumptions provide a type of solution based on the strength of the materials. Thereby, they will provide the basis for approaching the buckling of the bearing in tension in the presence of cavitation [14].

2. The effect of cavitation on the mechanical characteristics of rubber bearings

The onset of buckling instability in a multilayer bearing depends on the shear modulus G, on the effective compression modulus of the rubber–steel composite, E_c, and on the effective bending stiffness $(EI)_{eff}$, about the y-axis, of a rubber pad constrained between rigid layers [24,25]. Details on the derivation of the effective bending stiffness will be given hereafter.

When the hypothesis of incompressibility is valid, both effective compression modulus and effective bending stiffness of the material depend only on the shear modulus and on the cross-sectional shape of the bearing. For instance, consider a long strip bearing as shown in Fig. 2, with width $2b$, thickness of a single layer of rubber t, thickness of a single layer of steel reinforcing layer t_s, and h the height of the bearing without ending steel plates. The effective compression modulus of the rubber–steel composite is given by:

$$E_c = 4GS^2 \tag{1}$$

E_c is controlled by the first shape factor, S, which is defined as a dimensionless measure of the aspect ratio of the single layer of the elastomer, and by the shear modulus, G [26]. The analysis on an infinite strip bearing is conducted on a single pad of width $2b$ and fix length $a = 1$. For the long strip bearing shown in Fig. 2 the first shape factor is:

$$S = \frac{b}{t} \tag{2}$$

The moment of inertia I of the cross section $2b \cdot a$, about the axis of bending y, is calculated and then, by following the theory expressed by Kelly – see [27] for full derivations, the effective moment of inertia $I_{eff} = 1/5I$ is assumed. The one fifth factor arises from the cubical distribution of pressure that generates the resultant moment in the bearing. The bending stiffness of such bearing becomes:

$$(EI)_{eff}^{inc} = \frac{1}{5}E_c I \tag{3}$$

In the presence of cavitation, as a result of the increase in volume, the bulk modulus of the rubber in hydrostatic tension reduces, therefore it is essential to include the effect of compressibility in Eq. (1). The reduction of the bulk modulus depends, then, on how much the tensile strain exceeds the threshold for the initiation of cavitation, that here is assumed to correspond to a

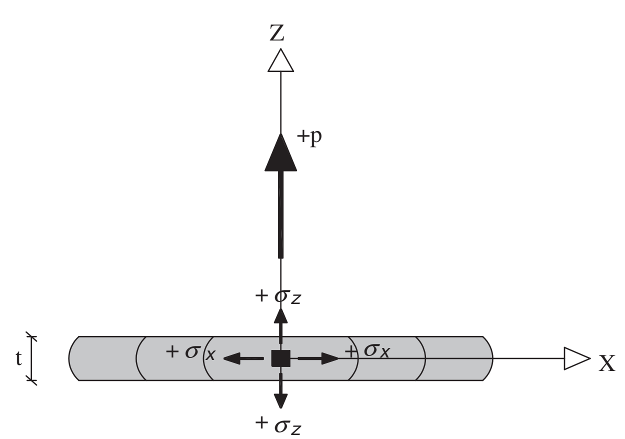

Fig. 1. State of tension stress in the centre region of a single layer of rubber.

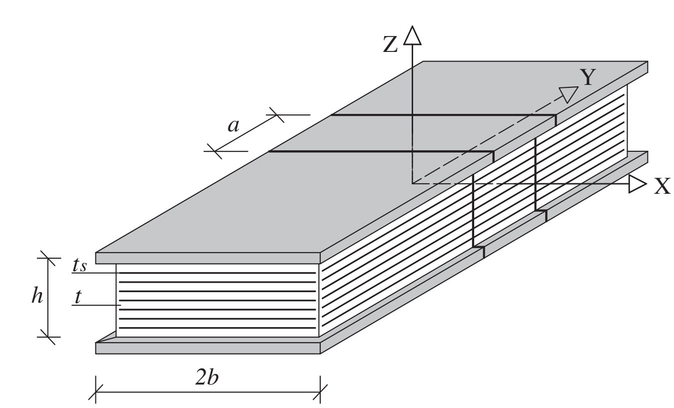

Fig. 2. An infinite strip pad of width $2b$, with n number of layers of rubber with height t and n_s number of layers of reinforced steel with height t_s.