Engineering Structures 174 (2018) 39–48

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental determination of the lateral stability and shear failure limit states of bridge rubber bearings

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ARTICLE INFO

Keywords:
Seismic isolation
Bridge rubber bearing
Buckling
Shear failure
Lateral stability tests
Limit states
Performance-based design

ABSTRACT

This paper aims to increase the existing experimental knowledge base concerning the limit states of performance of natural rubber elements that are typically used as bearing pads and seismic isolators for bridges. A large experimental study is performed on 13 reduced-scale and 11 full-scale natural rubber specimens subjected to different types of shear-compression tests. Both lateral stability and shear failure under realistic axial compression forces are addressed in the study, together with an investigation of different isolator sizes, shape factors and slenderness ratios. Stability curves are obtained from tests using the constant displacement method, and shear failure data from tests using the direct method are presented. Predictions of the critical buckling loads from different versions of the reduced area method are compared to the experimental stability curves, indicating that these commonly used estimates are not always conservative depending on the geometry of the bearing. Several buckling and shear failure test results obtained in this study specifically highlight the fact that the slenderness ratio is the most critical parameter when determining the ultimate limit states of rubber bearings, although this parameter is often neglected. The intermediate limit states before buckling or shear failure are also investigated. It is shown that such limit states of performance are nearly impossible to define experimentally because most bearings do not exhibit any visual damage before failure, although experimental data indicate that slight to moderate damage obviously occurs in bearings under large displacements.

1. Introduction

Performance-based design is becoming the calculation method of choice in the most recent standards and codes for highway bridges under seismic loading [1–3]. Such a design approach requires an appropriate knowledge of the intermediate and ultimate limit states of performance of each component of a bridge for a given seismically induced displacement. Rubber bearings and seismic isolators, which are often used in bridges, are made of successive, thin layers of rubber laminated with steel shims, resulting in lateral flexibility together with a large vertical stiffness. They are critical components in bridge systems during moderate and severe seismic events, because they must simultaneously sustain vertical loads and significant lateral deformation, which can range from 150% to more than 300% shear strain in the case of exceptional earthquakes. Under these ultimate conditions, an elastomeric device can either become unstable if it reaches a maximum lateral strength, beyond which its tangential stiffness becomes negative, or it can tear by shear failure. Other reported limit states are rollover for dowelled bearings [4] and failure under axial tension via cavitation for isolation bearings that are used for buildings or nuclear power plants, where significant overturning moments can generate external tension in the bearing [5]. Because the latter case is not expected to occur for bridges and since all isolators today are bolted through top and bottom external plates, these latter limit states are not investigated in this paper.

The first experimental studies on the ultimate limit states of elastomeric seismic isolators for bridges were conducted in the early 1990s, and they focused essentially on shear failure that occurred at very high shear strains around 600% [6–9]. With the exception of one specimen in Ref. [9], these studies dealt with synthetic rubber materials that were developed to resist extreme lateral deformation. This is not the case for most of the seismic devices used today in North America that are made

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https://doi.org/10.1016/j.engstruct.2018.07.039
Received 20 November 2017; Received in revised form 13 July 2018; Accepted 14 July 2018

of natural rubbers with extreme capacities of approximately 300% shear strain. In fact, there are only a few studies regarding the shear failure of natural rubber isolators, and there is actually a need for studies to improve this lack of knowledge in the current database.

In the 2000s, research focused almost exclusively on the lateral stability of natural rubber isolators. Several experimental studies were conducted to define experimental stability curves, which relate the maximum allowable lateral displacement to different levels of axial compressive forces for a tested specimen [10–14]. Instead of the more intuitive direct method, most of the experimental results were obtained using the very effective constant displacement method (CDM) developed in 1999 by Nagarajaiah and Ferrell [10] to specifically characterize the lateral stability problems of rubber isolators. Both of these methods will be explained further in this paper. The most commonly used shapes of bearings (i.e., square, circular and annular with or without a lead core) were all tested during these studies. The experimental results demonstrated, among other things, that the use of a lead core does not significantly affect the lateral capacity of a rubber isolator [12,14]. More recently, the study of Sanchez et al. [14] also demonstrated that the actual lateral displacement capacities of rubber bearings under dynamic loadings could be higher than those obtained using typically performed quasi static tests. Therefore, the experimental database for the buckling problems of natural rubber bearings still needs more research to produce a comprehensive understanding of other concerns that could affect the ultimate performance of these devices. Until now, the majority of the tests presented in the literature were conducted on reduced-scale specimens (generally with widths from 100 mm to 150 mm, the largest being 250 mm), and thus, more tests are needed on bearings with more realistic dimensions that are subjected to typical and practical axial loads. Only a few fully experimental parametric studies have been performed on bearing geometries [11] because such studies require tests on numerous specimens. Parametric studies are normally conducted using numerical approaches [15,16]. In addition, only the shape factor S (defined as the ratio of the bounded and vertically loaded rubber area to the free area of one rubber layer of the bearing) and similarly the rubber layer thickness t_r are generally considered to be relevant parameters to characterize the effects of bearing geometries on the lateral buckling capacity. Surprisingly, the effect of the slenderness λ of a bearing (defined as the ratio of the total rubber height to the width of the specimen) has rarely been explicitly discussed in recent experimental or numerical studies, although it was reported in the past (as could be trivially expected) to be a critical parameter that determines the type of failure for a rubber bearing (i.e., buckling or shear failure) [7]. The effect of the slenderness on the stability curve and critical lateral displacement of a bearing must still be clarified.

Previous experimental results have often been used to verify the validity of several analytical models and theoretical formulations to predict the critical axial loads of natural rubber bearings [10,15,17,18]. However, the current procedure used to estimate the critical load of a rubber isolator for a given lateral displacement is still based upon either Haringx's theory regarding the buckling of flexible columns under both flexure and shear [19–22] or the simplified analytical model developed by Koh and Kelly [23]. Both of these theories provide the same expression for the critical load P_{cr0} of a rubber bearing for small lateral displacements. The practical extrapolation of these theories to accommodate the large lateral displacements experienced by bearings is conducted by using the very simple reduced area method proposed in 1994 by Buckle and Liu [24] that applies a reduction factor to Haringx's critical load P_{cr0} according to the considered lateral displacement. However, this is an approximate method, and the experimental results of the abovementioned studies showed that this method is very conservative.

This paper is part of a research project that aims to qualitatively and quantitatively define the limit states of performance of rubber bearings that are useful to practical engineers for seismic isolation projects using a performance-based approach. To this end, a large experimental program was performed to determine the limit states of performance of square, natural rubber isolators. The experimental program comprises the study of 13 reduced-scale and 11 full-scale specimens subjected to shear-compression tests through either the direct method or the constant displacement method (CDM). Both the lateral stability and shear failure of isolators under realistic axial compression forces are addressed herein, including the examination of different isolator sizes, shape factors and slenderness ratios. First, the specimens, experimental procedures and experimental setups are presented. Then, the stability curves from tests that used the CDM and the results of shear failures from direct method tests are presented. Predictions of the critical buckling loads from different versions of the reduced area method found in the literature are compared to experimental stability curves. Considering the experimental results presented, a discussion is made about the observed influences of the geometrical parameters on both the lateral stability and shear failure. This discussion specifically highlights that the slenderness ratio λ is probably the most critical parameter when dealing with the ultimate limit states of rubber bearings. The intermediate limit states before buckling or shear failure are also investigated through experimental data. This paper mainly aims to add to the existing experimental knowledge base concerning the buckling and shear failure of natural rubber bearings by introducing new aspects about previous observations that can be found in valuable past studies.

2. Experimental setups and specimens

2.1. Experimental setups

Two experimental setups were constructed for this study in the structures laboratory of the University of Sherbrooke. The first setup was adapted for small-scale isolators (up to 150 mm wide), and the second setup was adapted for real-scale specimens (up to 500 mm wide). Both setups were defined to test specimens subjected to controlled quasi static axial loads combined with controlled shear deformation. Fig. 1 illustrates the experimental setup for the real-scale specimens (series A and B), which were tested individually. The axial loads were applied using a quasi static load frame with a 12 000 kN capacity, and the lateral deformation was imposed using a dynamic 500 kN-load and 750 mm-stroke actuator. During the test, the specimen was bolted to a fixed base frame, and accurate linear bearings between the transfer plates at the top of the specimen allowed for the simultaneous application of both vertical and shear loads. Roller bearings were also used to avoid any rotation of the transfer plates so that the top and bottom anchor plates of the isolator were always parallel. Load cells and an internal LVDT were used to measure the forces and displacements of each actuator. Two external horizontal potentiometers (one at each side) were used to measure the actual lateral displacement of the rubber bearing and to detect eventual in-plane rotations, and four vertical potentiometers (one at each corner) were used to measure the actual axial deformation of the specimen.

Fig. 2 shows the experimental setup used to test the small-scale specimens (series C, CS and CP) equipped with two dynamic 100 kN actuators with a 250 mm maximum stroke mounted perpendicularly. To simultaneously apply both shear and vertical loads, the isolators were tested using pairs of identical specimens, where each specimen was bolted to the testing frame on one side and welded together and connected to the shear actuator on the other side. The forces and displacements of each actuator were measured by load cells and internal LVDTs, and the actual lateral displacement of the isolators was measured using an external potentiometer.

2.2. Tested specimens

In the experimental study, 13 small-scale and 11 large-scale rubber