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A polynomial analytical model of rubber bearings based on series of tests

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ABSTRACT

Rubber bearings are among the most frequently applied devices in seismic isolation. Although the behavior of rubber bearings under strong earthquakes is nonlinear, it is often interpreted through the bilinear constitutive law. The investigations presented in this paper represent a successful attempt to simulate nonlinear force–displacement relationships. The first part of the paper covers production and testing of rubber bearings and results obtained. The second part deals with development of a simple nonlinear mathematical model of a rubber bearing involving a polynomial function and eight additional parameters obtained from biaxial tests. The polynomial model can simulate the behavior of natural rubber bearings in case of small and large deformations. The model is capable of covering the strengthening of the rubber in conditions of large deformations, including the loading history effect. Based on comparison between the analytical and experimental results, it is concluded that the proposed polynomial model is capable enough to simulate the force–displacement relationship of rubber bearings.

1. Introduction

One of the most effective techniques for design of earthquake resistant structures is application of seismic isolation. It is a collection of isolation units, which are to reduce the transfer of seismic energy to the upper structure. Over the last century, many isolation devices have been invented, but only a few of them have become popular. Out of these, rubber bearings are commonly used for isolation of buildings and bridges. The first application of a rubber isolation system took place in the sixties of the last century. A primary school in Macedonia was isolated by a system referred to as Swiss Full Base Isolation [22]. The basic concept of this system was providing a full 3D isolation by use of non-reinforced rubber bearings. Seismic isolation has practically become a reality with the development of multi-layered elastomeric bearings produced by simultaneous vulcanization of rubber and gluing of steel plates. The investigations done by Kelly [15,16], Naeim and Kelly [20] and Skinner et al. [21] have given a huge contribution to acquiring knowledge on the behavior of base isolated structures and different types of bearings. The application of base isolation of structures has been increased particularly after the Kobe (1995) earthquake [6], when good behavior of base isolated structures was observed [7]. Unfortunately, due to the high cost of the isolators, their application has long been limited to economically developed countries. However, today, even developing countries like Macedonia [8,9], and Armenia [18] are successfully producing and applying these devices.

To promote application of base isolation in R. Macedonia and the remaining countries in the Balkan, the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) proposed a project on development of low-cost rubber bearings [9], which was financed by NATO through the Science for Peace (SfP) Programme. Within this project, a number of raw rubber recipes and a technology for production of rubber bearings were developed for the first time in the region. Within this project, ample experimental tests were performed on bearings produced of 18 different rubber compounds. These tests enabled creation of a large database of force–displacement relationships for different rubber compounds that was later used for development of a new analytical model of rubber bearings.

The laboratory tests on rubber bearings which have been carried out within these investigations and the investigations performed by other authors [13,17,23], have pointed out their nonlinear behavior. The stress–strain behavior of rubber bearings is manifested by high horizontal stiffness under low shear strains, low stiffness under moderate strains, and an increasing shear modulus under higher strains. Usually, rubber hardening begins at 125% shear strain and continues until failure.

Lateral bearing behavior is quite complex because of strain-rate dependence and the presence of the Mullins effect [19], [12]. Other factors that have an influence upon the hysteretic behavior of

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rubber bearings are the axial load, ambient temperature, ageing effects and compounding. All these factors have resulted in complexity of hysteretic behavior of rubber bearings. Because of such complex behavior, the generally accepted modeling of bearings in horizontal direction by a bilinear model [5,20] cannot completely cover the actual bearing behavior. However, on the other hand, if all these factors are included in the analytical model of a rubber isolator, then this model will be ideal but also very complex.

To enable a more realistic dynamic analysis of structures isolated with rubber bearings, several advanced analytical models have been proposed in literature. One of the approaches is representing the nature of damping as hysteretic [17]. This model includes the high nonlinearity of shear strains but it does not include the strain rate and the effect of variation of the axial load upon the hysteretic properties of the bearing. The other approach includes implementation of the viscoelastic theory where the forces depend on the strain rate [13]. This proposed model is defined by ten parameters that are functions of the number of factors influencing the behavior of the elastomer. This model includes the Mullins effect, the strain rate and temperature dependence. The model proposed by Tsai et al. [23] also includes the effect of the strain rate. This model is based on the Bouce-Wen's model [2] which has been extended to seven material parameters and it can simulate high strain rate at low strains and strengthening of rubber at high strains. Another model where the hysteresis has the typical "butterfly" shape is proposed by Dall' Asta and Ragni [3]. In this model, the dependence on the strain rate and the Mullins effect are included, as well. The rate dependence has also been investigated and included in the model proposed by Jankowski [14].

The first phase of the investigations covered the development of rubber bearings and their testing. A comprehensive study was performed to develop the technological process of production of rubber bearings reinforced by steel shims. Providing quality of the end product and development of an appropriate recipe were one of the key tasks since such bearings were produced for the first time in the Balkan region. The quality of the end products was verified through a series of dynamic tests. In this part, the results from the vertical and horizontal tests carried out on a few characteristic bearings are presented through force–displacement diagrams.

The analytical polynomial model proposed in the second part of this paper was developed based on a series of tests on rubber isolators. Presented further in this part are the most characteristic ones. The proposed model can simulate the behavior of natural rubber bearings in conditions of small and large deformations. The model is defined by a polynomial function and eight parameters and it is able to cover the strengthening of the rubber in conditions of large deformations. It includes the loading history effect and enables adaptation to different shapes of loading/unloading. A least-square regression was used to determine the "best" coefficients in order to minimize the sum of the squares in an nth order polynomial model. System property modification factors for the effects of aging, temperature and scragging of rubber bearing [1] can also be included, if necessary. The consideration of the system property modification factors in this analytical model enables extension of the bilinear simplification [1] to the range of large deformations. This model can substitute the bilinear simplification of rubber bearings in the design procedure and was implemented in the finite element nonlinear program [11].

2. Production and testing of natural rubber bearings

One of the main goals of the NATO SfP project was development of a high damping rubber (HDR) compound, adoption of production of rubber bearings and their testing and implementation. The production of rubber bearings with different rubber compounds was carried out in a small local workshop in Macedonia. Eighteen natural rubber compounds were developed and used for production of more than 100 bearings. Two types of bearings were produced. The first was of a square shape, side length of 200 m and total height of 75 mm (Fig. 1b). The second was of a circular shape, external diameter of 150 mm and total height of 100 mm (Fig. 1c). The bearings pertaining to each type were produced without internal steel plates and with different number of steel plates.

Prior to the very process of vulcanization, the raw rubber was calendared to obtain rubber sheets with the required thickness. The internal steel plates, referred to as shims, were proportioned 190/190 mm and Ø140 mm. The first phase of treatment of the shims consisted of cleaning the sandblasted areas with medical gasoline. This helped remove all the dirt occurring from the moment of sandblasting to the moment of vulcanization. The second phase involved coating of the areas with an appropriate adhesive. This coating protects the steel areas against any external effects. After 2 h, the third phase took place, i.e., treatment of the steel areas with the second coat. As in the case of the first coat, after the second coating, the plates were also left to dry at room temperature for about an hour.

Upon completion of the preparation works, the tailored rubber and the treated reinforcement were inserted in a mold, which was previously heated to 120 °C. The rubber was vulcanized for 50 min at a temperature of 150 °C (Fig. 1a). In the course of the vulcanization, the rubber was constantly exposed, from the upper and the lower side, to external pressure of 150 bars. Once the vulcanization was over, the element was dismantled from the mold and left to cool at room temperature for 24 h.

After the production of the bearings, two types of tests were performed, namely vertical and biaxial tests. All the tests on rubber bearings were carried out in the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje. To perform the tests, the existing biaxial dynamic frame with a dynamic load capacity of $F_{MAX} = 100$ kN and stroke of $\Delta = \pm 75$ mm, was used. The static load capacity of the testing frame is $F_{MAX} = 200$ kN and the stroke is $\Delta = \pm 50$ mm. The set-up of the vertical and biaxial test is shown in Fig. 2a and b.

A detailed description of the selected tested specimens is given in Table 1.

Prior to each testing of the isolators, the materials were stabilized by keeping them under room temperature of (22 ± 2 °C) with a duration of 24 h. First, the isolators were pre-loaded with three cycles at low frequency. Such a pre-loading is practiced in testing rubber elements for the purpose of eliminating the Mullins effect [19]. Pre-loading is carried out exclusively for elements not loaded in the course of the preceding 24 h.

The procedure for the axial tests involved loading of the element with vertical compressive force at different axial stress levels (Fig. 3). The specimens were monotonically loaded up to the achievement of the necessary stress level when harmonic excitation was applied. The purpose of these tests was to define the effect of the number of internal layers upon the vertical stiffness of the bearings at different load levels.

Fig. 4 shows the vertical force–displacement relationship for the rubber bearings produced by different number of internal steel plates. The presented graph provides a thorough insight into the behavior of the bearings with and without layers. As expected, the bearing with the greatest number layers (four shims) exhibited the highest vertical stiffness.

For this series of produced bearings, the vertical stiffness at different axial load levels has been calculated (Table 2).

The biaxial tests consisted of application of horizontal load while the element was exposed to vertical load. The bearings were