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Sensitivity analysis on mechanical characteristics of lead-core steel-reinforced elastomeric bearings under cyclic loading

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ABSTRACT

This research conducts a sensitivity analysis on the mechanical properties of lead core rubber bearings (LCRBs). Here, the input variables include: number of rubber layers, lead core radius and lead core material properties. A full factorial numerical experiment is designed and the hysteretic behaviour of a total of 81 LCRBs with varying parameters is captured through numerical simulation. The material models used in those models were first validated with experimental results from published literature. Operational characteristics of the studied bearings include: the vertical and horizontal stiffness, and the equivalent viscous damping ratio. An analysis of variances is then conducted in order to quantitatively express the effectiveness of each parameter. Among the three considered input variables, the lead core radius is the most dominant parameter in affecting LCRBs' performance, whereas the number of rubber layers has the least contribution. It is observed that the lead core influences bearing's vertical stiffness the most, compared to other input variables.

1. Introduction

Isolation techniques have been helping building and bridge structures operate safer and withstand stronger earthquakes since as early as 1970s [1]. For the past three decades, different isolation devices have been introduced and implemented in real-life practice and have shown to be successful in terms of saving structures from severe damages [2,3]. Base isolation systems are intended to shift the natural frequency of the structure far enough from the excitation frequency, as a consequence of which the structure will experience less structural and non-structural damages. Base isolators are used for a wide range of purposes. They are not only used to decouple the structure from ground vibrations, but also are implemented to accommodate pre-stressing relaxations, thermal movements, shrinkage and time-dependent phenomena such as creep [4,5].

Seismic isolation bearings can be mainly categorized as friction-based and elastomeric types. Friction Pendulum System (FPS) and Flat Sliding Bearing (FSB), falling into the former category, are designed to dissipate the earthquake energy through friction between bearing elements. FPS provides the structure with a pendulum motion associated with friction, thanks to a concave-shape dish and a housing plate [6]. These two characteristics (i.e., friction between bearing elements and pendulum motion) are the fundamental factors that define the isolation properties [7]. Elastomeric bearings, on the other hand, dissipate the energy through hysteresis response of rubber and their auxiliary elements, if any. Auxiliary elements used in rubber bearings include, but are not limited to, lead, shape-memory alloy (SMA) and fiber-reinforced polymer. A brief literature review on such bearings is given in Section 2 of this article. Methodologies are also proposed to use a combination of the mentioned isolation techniques [8,9].

Despite the numerous research conducted on different isolation systems and, particularly, lead-core rubber bearings (LCRBs), limited research has been conducted on the performance sensitivity of such bearings to their mechanical and material properties. Therefore, in this study, LCRBs are focused on and a comprehensive sensitivity analysis is designed and performed in order to pave the way for further research. To this end, performance of LCRBs is investigated through numerical study using material properties validated with experimental results from the literature. The effects of three input variables including the number of rubber layers, lead plug radius and lead core material properties are studied for three shear strain levels, for a total of 81 designed configurations. The effects are shown in terms of bearings' operational characteristics, including their vertical and horizontal stiffness, and their energy dissipation capacity. A sensitivity analysis is conducted in order to quantitatively express the results. Hysteretic behaviour of bearings is

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captured under different shear strain levels. Hysteretic damping ratio provided by the bearing is also acquired and a comparison is drawn in order to highlight the effect of each parameter. Finite element method is used to conduct the aforementioned analyses and Analysis of Variances (ANOVA) is implemented to interpret the results.

2. Rubber bearings

Isolation rubber bearings, based on their characteristics and components, are classified into different categories. Considering the rubber material, they can be categorized into low-, natural-, and high-damping rubber bearings (LDRB, NRB and HDRB in short, respectively). Auxiliary elements are occasionally added, in order to improve isolators' performance and make them more suitable for various purposes. Lead, fiber-reinforced polymers, and smart materials such as shape memory alloys (SMA) are auxiliary components that are implemented in rubber bearings. Their effectiveness is demonstrated through various numerical and experimental investigations conducted by researchers and practitioners. Based on the supplementary elements, they can be categorized as lead-core rubber bearings (LCRB), fiber-reinforced elastomeric isolators (FREI) and SMA-lead rubber bearings (SMA-LRB). Fiber-reinforced polymer, as a material with uni- or bi-directional behaviour, high strength and lighter weight compared to steel, has been suggested to be used as an alternative to steel reinforcements in elastomeric bearings [10,11]. It is shown that this material, which is flexible in extension and has no flexural rigidity, can perform as satisfactorily as, if not better than, steel shims as reinforcements in isolators. Hedayati Dezfuli and Alam have shown the effectiveness of carbon fiber-reinforced polymers in elastomeric isolators (C-FREI) through a sensitivity analysis and a multi-criteria optimization study, and then implemented them into an isolated steel girder bridge with reinforced concrete piers [12,13]. FREIs can be manufactured in the form of long strips with variable widths. Any desired bearing size can then be cut out using a band-saw, water jet technology or other appropriate machines. In addition, they can be manufactured using a cold vulcanization practice through which no mold and hot vulcanization process is involved [13]. These facts, all together, ease bearings' manufacturing process considerably and give rise to their popularity. The use of such auxiliary elements has not been limited to elastomeric bearings. For instance, Cardone et al. have proposed displacement-based design procedures for elastomeric bearings, Friction Pendulum Systems and combinations of sliding bearings with auxiliary devices such as SMA [14].

Choi et al. evaluated the behaviour of a newly-proposed rubber bearing enhanced with SMA wires, called SMA-rubber bearing [15]. Hedayati Dezfuli and Alam proposed different configurations of SMA wires in rubber bearing isolators, called Smart Rubber Bearings [16]. Bhuiyan and Alam investigated the performance of smart isolation bearings equipped with two types of super-elastic SMAs and evaluated their efficiency in mitigating vibrations and damages of highway bridges during moderate and strong earthquakes [17].

An un-bonded bearing application (without top and bottom steel supporting plates) is also introduced in the literature, in which the bearing is freely placed between the structure and its lower support, and is not attached to the structure by bolts, fasteners or any other means. Toopchi-Nezhad et al. have investigated the effectiveness of such un-bonded isolators and have shown that their hysteretic behaviour is comparable to, or even in some cases more efficient than, that of conventional isolators [18].

2.1. Lead-core rubber bearings (LCRBs)

Isolation bearings have to exhibit three main features: 1) a desired lateral flexibility, 2) a sufficient vertical stiffness and 3) a high energy dissipation capability. In regular rubber bearings, these three responsibilities are carried out by rubber and steel shims. However, adding a lead plug to the bearing system augments its performance significantly. The lead plug contributes to having a higher vertical stiffness. Besides, it enhances the energy absorption capacity and adds hysteresis damping to the system since it undergoes an inelastic deformation. As the lead plug goes beyond elastic deformation, structure's stiffness decreases and, as a consequence, the natural period of the structure, which is inversely related to the stiffness, increases. The lead plug also offers an

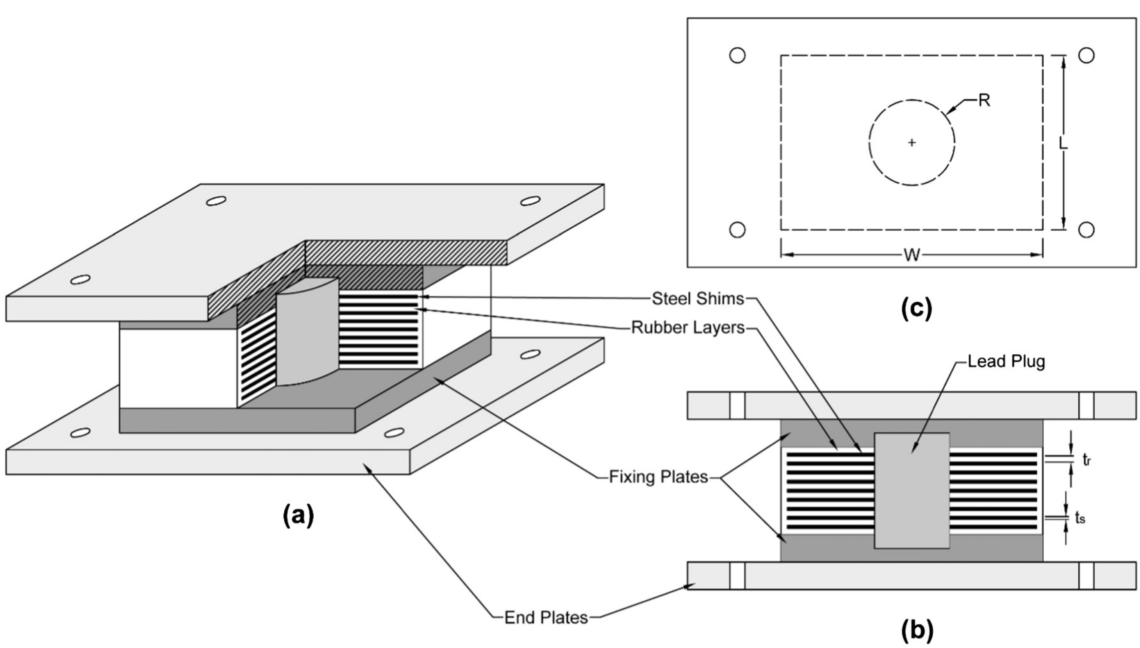

Fig. 1. Schematic view of (a) lead-core rubber bearing and its components, (b) Side view and (c) Plan view.