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Seismic performance assessment of highway bridges equipped with superelastic shape memory alloy-based laminated rubber isolation bearing

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ABSTRACT

Seismic performance analysis is conducted for an isolated three-span continuous highway bridge, which is subjected to moderate to strong earthquake ground accelerations in the longitudinal direction. Two types of isolation bearings are used in the analysis: high damping rubber bearing (HDRB) and combined isolation bearing consisting of shape memory alloy (SMA) wires and natural rubber bearing (NRB) entitled as SMA-based rubber bearing (SRB). Two types of SMA wires, such as Ni–Ti and Cu–Al–Be, are used in fabricating the combined isolation bearings. In the first step of the work, analytical models for HDRB, NRB and SRB are introduced. Then, a three-span continuous highway bridge is modeled in a simplified form, using 2-DOF bridge pier-bearing system isolated by either HDRBs or SRBs. The hysteretic behavior of HDRB is evaluated using a strain-rate dependent constitutive model (i.e. visco-elasto-plastic model), while in the case of SRBs the hysteretic behavior is modeled by a nonlinear elasto-plastic model for NRB and a simplified visco-elastic model for SMAs. A standard bilinear force–displacement relationship is employed in the analytical model of the bridge pier to consider its nonlinear characteristic behavior. Nonlinear dynamic analysis of the bridge, based on the direct time integration approach, is conducted to evaluate the seismic responses of the bridge. This study shows that the seismic responses of the bridge are affected by the use of different types of isolation bearings; more specifically, residual displacement of the deck are noticeably reduced after earthquakes in the case of SRBs compared to HDRB for moderate and strong earthquakes; however, pier displacements are smaller in the cases of SRBs for moderate earthquakes and higher for strong earthquakes. Other response parameters of the system, such as deck displacement, bearing displacement and deck acceleration, are significantly larger in the cases of SRBs compared to those of HDRB. This study also depicts the effect of modeling of isolation bearings on the seismic responses of the system.

1. Introduction

Seismic isolation has been considered as a reliable and cost-effective technology to alleviate the risks of seismic damages to highway bridges [1–5]. In Japan and United States, more than 200 bridges have been designed or retrofitted with seismic isolation devices in the last 20 years, for example, the 29-span continuous O-Hito viaduct in Japan and the 7-span continuous steel girder Lake Saltonstall bridge in USA. Seismic isolation is meant to shift the natural period of a bridge structure in such a way that the dominant frequency of the earthquake ground acceleration can safely be avoided to safeguard it against seismic damages. In addition, the inherently occupied damping property and energy dissipation mechanism prevents the bridge system from over displacement [5]. Field data on the seismic response of isolated bridges during recent earthquakes [6], experimental works [7–11] and analytical studies [7,8,10,12–16] have indicated that isolation bearings can substantially improve the seismic performance of bridges and consequently reduce the post-disaster cost for repair and rehabilitation [17].

Two types of seismic isolation bearings are mainly available for this purpose: laminated rubber bearings and sliding bearings. The sliding bearings show reasonably good performance under a wide range of earthquake loadings and have been applied in both buildings and bridges [18]. They are insensitive to the frequency content of earthquake excitations as they can suppress and widen the earthquake energy over a large range of frequencies [19]. The sliding-type bearings have several deficiencies over laminated rubber bearings. For instance, (i) large maintenance of sliding surface is expensive and difficult as lubrication is required while in service; (ii) difficult to mount and erect due to its large size and heavy

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weight; (iii) occurrence of large relative displacement between bridge deck and pier as it does not have re-centering capacity, and (iv) a stopper is essential. On the other hand, laminated rubber bearings have the ability to carry vertical loads in compression and accommodate shear deformations [1]. The rubber layers reinforced with steel shims (Fig. 1) reduce the freedom to bulge by increasing the vertical stiffness of the bearing. Three types of laminated rubber bearings are widely used as seismic isolation devices: natural rubber bearing (NRB), lead rubber bearing (LRB), and high damping rubber bearing (HDRB). Natural rubber bearings are inherently flexible (i.e. reduced stiffness) and possess small damping property. Hence, NRBs have been utilized to accommodate the thermal movement, the effects of pre-stressing, creep, and shrinkage of superstructure of highway bridges or for seismic isolation by combining with other energy dissipation devices such as lead, steel and viscous damper [1,5]. Other two types of bearings acquire high damping, which are developed and widely used in various civil structures including bridges in many countries, especially in Japan and USA [1,4,5]. Although the schematic of HDRB and NRB are the same (Fig. 1), HDRB uses high damping rubber whereas NRB uses natural rubber. HDRBs possess a variety of mechanical properties, which are influenced by their compounding effects [7] (i.e. the chemical composition of rubber chain, which is fully controlled by the manufacturer; for instance, in high damping rubber, a special fluid is used in the fabrication process to increase its damping property), nonlinear elasto-plastic behavior [1], temperature and strain-rate dependent viscosity property [5,20–22]. Lead rubber bearings also acquire all the mechanical properties of HDRB with reduced extent [23]. The unfortunate coincidence of the natural period of a seismically isolated bridge with that of the near field earthquakes may enhance its seismic responses significantly. Especially, laminated rubber bearings may experience large horizontal deformation under near field earthquakes, which may cause detrimental problems such as instability of the bearings, unseating and pounding problems of the bridge deck [14,24].

In recent years, a number of attempts have been reported, by combining natural rubber bearing (NRB) and shape memory alloy (SMA) in seismic isolation of highway bridges, to partially solve the problems incurred by laminated rubber bearings [14,15,24–27]. The superelasticity accompanied by hysteresis property of the SMA allows it to fabricate with laminated rubber bearings to reduce the residual deformation of the bridge system. Considering the restoration and energy dissipation capacity of SMAs, they are gaining wide interests in the research community for seismic protection of highway bridges. Ozbulut and Hurlebaus [14] conducted a sensitivity analysis to examine the effectiveness of an isolation system consisting of SMA device and natural rubber bearing (SRB) for seismic protection of highway bridges. They utilized a neuro-fuzzy model to replicate the superelastic behavior along with re-centering capability of SMAs at various temperatures and loading rates, and a linear equivalent method for modeling hysteresis behavior of natural rubber bearing, which were then applied in evaluating the seismic performance of a three-span continuous bridge. They showed that the isolation system can successfully reduce the deck drift of highway bridges. Wilde et al. [15] used SMA bars coupled with elastomeric bearings for bridges in transverse direction and demonstrated that the SMA bars with elastomeric bearings are effective device to control relative deck displacement. Choi et al. [24] proposed a new isolation bearing that consist of natural rubber bearing and pre-stressed Ni–Ti SMA wires that wrap the bearing in the longitudinal direction. Dynamic time history analyses were conducted using two earthquake ground accelerations on multi-span continuous highway bridge to evaluate the effectiveness of the proposed bearings where each record was scaled up to 0.8 g. The performance of the new bearing was compared to that of a conventional lead rubber bearing. They showed that the new bearing provides adequate damping properties and centering capability, which restricts the relative displacement of the bridge. DesRoches and Delemont [25] utilized SMA bars as restrainers in a multiple span simply supported isolated bridge with elastomeric bearings and showed that the SMA bars can more effectively restrain the relative deck displacement compared to the conventional steel cable restrainers. Johnson et al. [26] carried out large-scale shake table testing to estimate the performance improvement of SMA restrainers fitted in an isolated multi-frame box girder bridge under seismic loading and compared their performance with traditional steel restrainers. Casciati et al. [27] developed an isolation system consisting of sliding system and inclined Cu–Al–Be SMA, and conducted extensive experiments on a prototype device to illustrate the effectiveness of using the new device in dissipation of energy and re-centering capability. Recently, Alam et al. [28] and Bhuiyan and Alam [29] have carried out performance evaluation of multi-span continuous highway bridge isolated by an isolation bearing consisting of high damping rubber bearing and Ni–Ti SMA restrainers, and demonstrated the effectiveness of the bearing in seismic responses of the bridge.

Several researchers have utilized SMAs for outdoor applications, for instance, Wilde et al. [15], Choi et al. [24] used superelastic Nitinol for base isolation of bridges; however, temperature effect was not considered in those studies. In cold region country like Canada temperature can range from −50 °C to +40 °C in some places. Usually Nitinol's austenite finish temperature (A_f) ranges from −10 °C to 44 °C [30], which clearly demonstrates its potential of losing superelasticity if the temperature goes below its A_f where the system will lose its recentering capability. Therefore, SMAs having A_f below −50 °C might be a better choice for outdoor applications. For instance, Zhang et al. [16] utilized superelastic Cu–Al–Be bar with A_f of −65 °C. They numerically showed the effectiveness of superelastic Cu–Al–Be restrainer for bridges. Alternatively, at low temperatures regular SMA can also be used with the help of a control system where in the case of an excitation, the SMA wires will be automatically electrically heated above its A_f to trigger its superelasticity [31]. Considering the thermomechanical properties of SMAs as mentioned above, previous researchers have proposed two different SMAs i.e. Ni–Ti and Cu–Al–Be for isolation and restrainer applications.

In all these previous attempts, natural/lead rubber bearings (NRBs/LRBs) were mostly employed in constructing their proposed SMA based isolation bearings. Moreover, either the equivalent linear model or the bilinear model [32,33] was adopted to analytically describe the mechanical behaviors of the NRBs/LRBs. However, it has been experimentally evident from the previous works

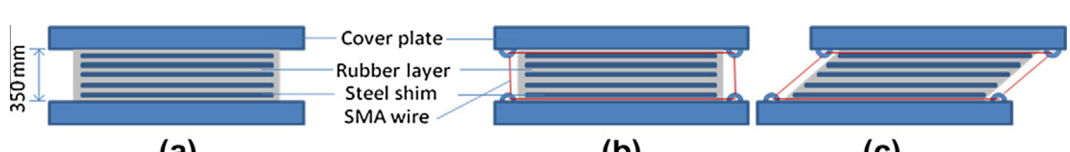

Fig. 1. Description of the isolation bearing (pad 1000 mm × 1000 mm with 350 mm height) (a) HDRB; the rubber layers with high damping properties are vulcanized by steel shims, (b) SRB in un-deformed condition and (c) SRB in deformed condition.