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Seismic response of a continuous bridge with bearing protection devices

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ABSTRACT

Unseating of bridges during earthquakes results from the failure of bearings and insufficient seat length. In case of elastomeric bearings, large deformations of the superstructure occur, under severe earthquake ground motions and additional protection measures are necessary. The combination of a displacement restraining device with the elastomeric bearing can prevent bearing failure. This paper evaluates the performance of four different types of protection devices to limit the displacement of the superstructure during earthquakes: (1) rigid stopper device, (2) yielding stopper device, (3) steel restrainer, and (4) superelastic shape memory alloy (SMA) restrainer. Analytical models for all the protection devices have been developed and seismic response of an existing bridge with elastomeric bearings and different protection devices has been evaluated for five strong ground motion records scaled in the frequency domain. The results show that all the protection devices have comparable performance in preventing the failure of bearing during an earthquake.

1. Introduction

Failure of bridges due to excessive displacement of superstructure or inadequate seat length at the pier or abutment is a common phenomenon during earthquakes. In case of elastomeric bearings [1–3], which do not have any energy dissipating characteristics, the displacement during a severe earthquake is quite large and may exceed the capacity of the bearing, resulting in failure of the bearing [4] and unseating of the superstructure. Measures to reduce the chances of collapse due to unseating at the supports have been available for many years [5]. But, in spite of that, the collapse of the bridges due to unseating continues and the Chi–Chi [6], Kobe [7], San Fernando [8] and Northridge [9] earthquakes have shown several examples. Therefore, there is a definite need to explore better methods of protection of bridges against unseating failure during earthquakes.

Restrainers and stoppers are used as the protection devices to prevent the failure of bridges due to unseating [10,11]. Various design approaches for restrainers are available in literature [12–14] and design codes [15–17]. In all the approaches, the focus is on the prevention of falling of the superstructure and no attention is given to the prevention of the failure of bearings. In the present study, the possibility of restrainers designed to prevent failure of the bearings during severe earthquakes has been explored. Using this approach, the bearing protection devices can be designed for new bridges, as well as, for existing bridges. In case of existing bridges, this method can be used if the existing bearings are not able to accommodate large displacement due to strong earthquake. In case of older bridges, the most widely used bearings are elastomeric bearings and these are generally designed only for movements arising due to temperature, creep and shrinkage. Use of restrainers/stoppers can be an effective technique to prevent failure of these bearings during earthquake.

The proposed method can also be useful for new bridges, if the designer does not have confidence in the use of isolation or energy dissipation devices and is inclined to use conventional elastomeric bearings. If the elastomeric bearing is designed for severe earthquake (MCE) it may lead to very large size of the bearing which is not practically acceptable in respect of required pier cap dimension. Reduction of the size of the elastomeric bearing may lead to failure, during an MCE level of earthquake. Therefore, restrainers/stoppers can be used with the elastomeric bearings to prevent failure of the bearings during severe earthquake.

Several types of devices, such as, steel rods, steel cables [18,19] and dampers have been used as the unseating protection devices for bridges. Shape Memory Alloy (SMA) has also been used in bridges as an unseating protection device [20–25]. Various devices have relative merits and the designer has difficulty in selecting the most appropriate device.

In this paper, the comparative performance of different types of unseating protection devices has been studied for a continuous bridge. All the devices have been designed to prevent failure of bearings. Four types of devices have been considered in the study: (1) rigid stopper, (2) yielding stopper, (3) traditional steel

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Nomenclature

DBE	Design Basis Earthquake
MCE	Maximum Considered Earthquake
F	Force
F_y	Yield Force of the Protection Device
K	Stiffness of the Protection Device
Δ	Displacement
Δ_i	Initial Slack/gap in the Protection Device

restrainers, and (4) Shape Memory Alloy (SMA) restrainer. A three dimensional model of the bridge has been developed using the software SAP2000 Nonlinear [26]. A set of five accelerograms, compatible with the site specific design response spectrum has been used for study of the seismic response.

2. Unseating protection devices

Different types of unseating protection devices, viz. rigid stopper, yielding stopper, steel restrainer and SMA restrainer, have been explored in the past. All these devices can be used along with the elastomeric bearings. The rigid stopper has a very high strength and stiffness and is provided with a gap from the superstructure, coming into action after a certain amount of displacement of the elastomeric bearing and stopping further displacement (Fig. 1). A yielding stopper [27] and a steel restrainer have a similar behaviour but the initial stiffness and yield strength are different for the two devices. These devices yield at a particular force, and then undergo strain hardening (Fig. 2). In the case of SMA restrainer devices [28–33], Nitinol shape memory alloy is the most commonly used material. Shape memory alloys display several remarkable characteristics like thermo-mechanical phase change, shape memory effect, superelastic effect and high damping. Shape memory effect has been observed when the alloy is loaded at a temperature below a specific temperature (martensite finish temperature). In this case, the residual strain can be recovered by heating the material to a temperature above the austenite finish temperature. A superelastic effect (Fig. 3) has been observed when the material is loaded at a temperature above the austenite finish temperature. In this case, during unloading, the material recovers all of its residual strain. The superelastic effect in the shape memory alloy is the property used in restrainer devices.

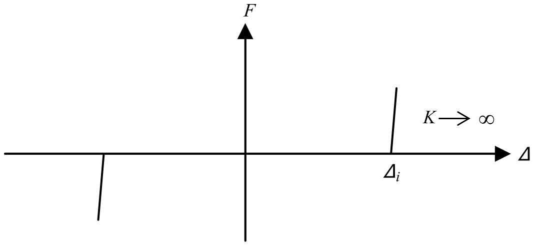

Fig. 1. Force–displacement behaviour of a rigid stopper device.

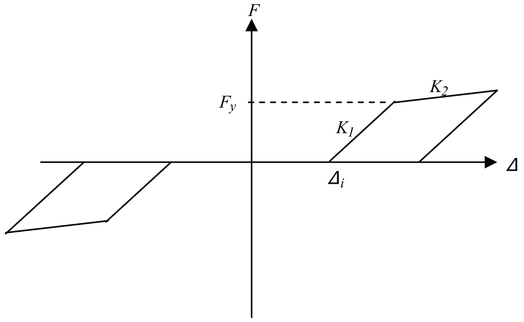

Fig. 2. Force–displacement behaviour of yielding stopper and steel restrainer devices.

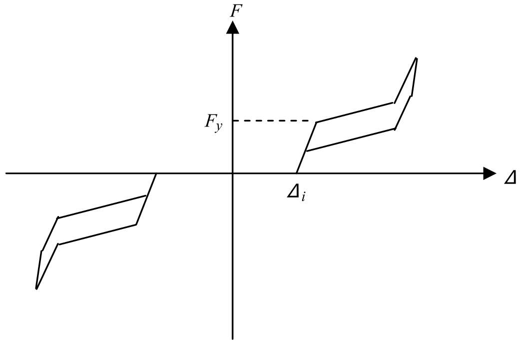

Fig. 3. Force–displacement behaviour of superelastic SMA restrainer device.

3. Bridge considered for the study

An existing three span railway bridge, situated in Northern India, has been considered in the present study. The site of the bridge falls in the Seismic Zone IV of the Indian seismic zoning [34]. It is a continuous prestressed concrete box girder bridge, having a total length of 192 m with the main span of 80 m and two end spans of 56 m each (Fig. 4). The cross-sectional details of box girder are shown in Fig. 5. The height of the piers is 36.36 m. The piers have a hollow circular section with an external diameter of 6.5 m and thickness of 0.5 m. The piers rest on rocky strata.

4. Modelling and analysis

The bridge structure has been modeled (Fig. 6) using the software SAP2000 Nonlinear. The superstructure and the piers have been modeled using 3D frame elements with mass lumped at discrete points. Since the piers are resting on rock, these have been modeled as fixed at the base. The abutments have been assumed to be rigid. To model the spatial placement of bearings across the section, horizontal cross rigid links as shown in Fig. 6 have been used. Elastomeric bearings have been modeled using elastic link elements. The rigid stopper has been modeled using a link element having high stiffness, whereas the yielding stopper and the steel restrainer have been modeled by elasto-plastic bi-linear link elements. The behaviour of the superelastic SMA restrainer (Fig. 7(a)) has been modeled through the parallel combination of two elastic multilinear link elements and one plastic bilinear element, which is in series with a hook element (Fig. 7(c)). The multilinear link elements have been assigned elastic stiffness in both the horizontal directions and are rigid in the vertical direction. The schematic modeling of the superelastic SMA restrainer in both the longitudinal and transverse directions has been shown in Fig. 7(b).

The site-specific design response spectra for Maximum Considered Earthquake (MCE) and Design Basis Earthquake (DBE) have been considered in the study. Fig. 8 shows the site specific design response spectra for 5% damping. Recorded time histories for five different earthquakes have been used and scaled in the frequency domain, to simulate the design response spectrum [35], preserving their phase information. The scaled time histories for MCE loading condition have been shown in Fig. 9. The recorded earthquakes considered are: (1) Elcentro (1940), (2) Kobe (1995), (3) Northridge (1994), (4) Loma Prieta (1989) and (5) San Fernando (1971). The details of the earthquake records have been presented in Table 1.