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Seismic performance of Transverse Steel Damper seismic system for long span bridges

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ABSTRACT

To provide seismic resistance of long span bridges in transverse direction, fixed bearings are often installed between girders and piers (or towers). Although the fixed bearings and substructures can be designed extraordinarily strong to resist the design seismic loads, they may still be vulnerable when the design seismic loads are exceeded. To address this issue, this paper proposes a novel seismic system, which combines Transverse Steel Dampers (TSDs) with conventional sliding bearings, and is named the TSD seismic system. A TSD consists of several triangular steel plates outfitted with steel hemispheres at their upper vertices. The steel hemispheres not only allow free movements of the superstructures with respect to the piers in the longitudinal direction, but also provide reliable load paths in the transverse direction. Quasi-static tests have been conducted to investigate seismic behaviors of the TSD using two scaled and two prototype specimens. Test results show that the TSD has excellent performance in energy dissipation, large displacements, and synchronization of triangular plates under complex contact conditions. The load-displacement constitutive model of the TSD has been established using a bilinear model in ABAQUS, followed by a design method for the TSD seismic system. A 620 m long-span cable-stayed bridge was selected for a case study of the TSD seismic system. Ground motions recorded at various site conditions were used as seismic inputs. Numerical results show that: (1) the TSD seismic system can achieve a desired balance of transverse seismic displacements and forces, which is not the case when a sliding bearing system (without TSDs) or a fixed bearing system is used; (2) TSDs contribute to most of the energy dissipation capacity of a TSD seismic system while the contribution of sliding bearings is negligible; and (3) the proposed TSD seismic system, compared with a sliding system, tends to be less sensitive to seismic input properties, such as peak ground accelerations and site conditions.

1. Introduction

Sliding and fixed bearing systems have been commonly used in the transverse direction of long span bridges to resist lateral seismic excitation. In areas of low seismic intensities, the sliding system is a common choice. Specifically, anchor bolts that constrain the movement of bearings in transverse direction under service loads are designed to fail when seismic forces exceed their design capacities. However, in areas of high seismic intensities, the sliding system is not appropriate because displacements between girders and piers may exceed their design levels, resulting in higher possibility of unseating. Therefore, the fixed system is used most often to constrain the transverse movements. Three issues should be considered when a fixed bearing system is used. Firstly, large transverse forces would develop in piers and foundations, which inevitably lead to over-sized structural members and high costs. Secondly, large transverse forces could also develop in the bearings, which increase design requirements and costs for the bearings. Thirdly, bearings, piers and foundations could still be damaged when the magnitudes of actual earthquakes exceed design values [1,2]. In order to achieve more balanced transverse forces and displacements between the girders and piers in long span bridges, different types of seismic devices are needed. A discussion of previous representative work on seismic devices follows.

Friction Pendulum Sliding Bearings (FPSBs), Viscous Fluid Dampers (VFDs) and Metallic Yielding Dampers (MYDs) have been commonly used on bridges to mitigate seismic demands. The energy dissipation capacities of FPSBs mainly depend on the magnitude of vertical dead loads [3]. Therefore, they are not suitable for the

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cases that the vertical dead loads are relatively small. In long span bridges, VFDs are commonly used as seismic devices in the longitudinal direction and have been studied extensively in recent decades. The Rion-Antirion cable-stayed bridge in Greece [4] used VFDs in the transverse direction. However, complex structural details are required to decouple the VFDs from longitudinal movements of the bridge, thus making it difficult to be widely applied for transverse seismic protection. Since Yao [5] firstly proposed the concept of structural vibration control, a series of energy dissipation mechanical devices and dampers, collectively known as the structural protecting system, have been developed. MYDs, proposed by Kelly [6] were initially introduced as passive control devices in structural engineering. Currently, MYDs are most commonly used in buildings, even though there have been some application in bridges with relatively short spans. MYDs can be categorized into four types based on different mechanisms: torsion, bending, axial tension and compression, and shear. Torsional beam devices [7,8] were used for providing base isolation on Rangitikei Rail Bridge in New Zealand (a 56 m simple-supported girder bridge). Steel cantilever beam devices [9] were used on Cromwell Bridge in New Zealand (a 60 m steel truss bridge). Tapered cantilever dampers [10,11] were installed on Dunedin Motorway Overbridge in New Zealand (a 52 m simply-supported girder bridge). Shaft elements and frame-type devices [12] were used on Mortaiolo Bridge in Italy (a continuous concrete girder bridge). C-type devices [13] were installed on Bolu Viaduct in Turkey. In summary, most of the MYDs were applied in the longitudinal direction of bridges with relatively short spans. When the MYDs are used in the transverse direction of long span bridges, there are many issues need to be addressed, which include: ultimate strengths; displacement capacities; space constraints; accommodations to longitudinal movements of girders; deformation accommodations due to temperature variations of concrete; shrinkage and creep. Because of these challenges, novel seismic devices to mitigate transverse seismic demands for long span bridges are in great demand.

A Transverse Steel Damper (TSD) seismic device is presented in this paper. Theoretical and experimental studies were conducted for the TSD. A design method for the proposed transverse seismic system (called TSD seismic system) consisting of the TSD and conventional sliding bearings is proposed. A real 620 m long span cable-stayed bridge was selected for a case study to validate the feasibility of the design method and the effectiveness of the TSD seismic system. Seismic performance of the TSD seismic system was analyzed and compared with conventional sliding or fixed systems.

2. Transverse Steel Damper (TSD)

2.1. Problem descriptions

One of the key issues of seismic devices is the choice of appropriate components for energy dissipations. Past studies [14–17] have verified that triangular-shaped and X-shaped plates possess excellent energy dissipation capacities, because the sections along the heights of such plates can develop full plasticity simultaneously. Dampers with these types of plates have been used extensively in buildings for seismic mitigation and retrofits. However, considering the differences in load paths and spatial constraints between buildings and bridges, these types of dampers, though proven to be effective for buildings, could not be directly used on bridges. Firstly, the inertial forces are almost linearly distributed along the height of a regular building. Base shear forces and story drifts are most influential parameters in the seismic design of buildings. While for bridges, inertial forces are primarily generated by superstructures and then transferred to substructures through bearings. The seismic forces in bearings, piers and foundations, and the relative deformations between girders and piers are key parameters in the seismic design of bridges. Secondly, dampers are placed between floors in buildings, whereas on bridges, they are installed in the much narrower spaces between girders and piers. Thirdly, dampers in buildings do not experience appreciable deformations in operating conditions, while in bridges, transverse dampers need to accommodate longitudinal displacements of the girders under normal operational conditions, resulting in complex configuration of the dampers.

Considering the issues of existing seismic devices, the proposed TSD should have the following features: (1) adaptability to longitudinal displacements of the bridge without affecting the transverse energy dissipation capabilities; (2) fit within limited spaces between girders and piers; (3) reliable load paths during earthquakes; and (4) mathematical constitutive models that can be easily verified using finite element method. Also, since non-uniform seismic demands may cause bridges to rotate in plane and lead to torsional failures of the X-shaped dampers [18], the proposed TSD uses triangular plates to reduce the probability of torsional failures.

2.2. TSD configurations

The configuration of the TSD is illustrated in Fig. 1. It consists of two parts. The upper part is bolted to the underside of girders. The steel blocks of the upper component are designed sufficiently stiff to transfer inertial forces to the triangular plates of the lower part. Design provisions on the height of the steel block (H_s in Fig. 1(d)) are discussed in Section 2.3.1. Polytetrafluoroethylene (PTFE) slides are attached to steel block surfaces to facilitate the sliding of hemispheres. The lower part is bolted to the top of piers or cap beams. The triangular plates are welded to the base plates. The hemispheres are installed at the vertices of the steel plates and in contact with the steel blocks with the help of PTFE slides. Note that for installation convenience, small gaps between the steel blocks and the hemispheres are allowed. There are circular holes at the vertex of each triangular plate and center of each hemisphere to allow for bolted connections. Earthquake-induced lateral forces in superstructures are transferred from the upper part to the lower part through contacts between the hemispheres and steel blocks. Triangular plates can be made of steels that are commonly used in bridges with desired strengths and stiffness.

2.3. Theoretical mechanical properties

As illustrated in Fig. 1(d) and (e), considering a lateral force F acting on the vertex of one triangular plate through the hemisphere, the edge stress, σ, of any section that is x meters away from the vertex can be determined as follow:

$$\sigma = \frac{Fxt/2}{(1/12)(x/H)Bt^3} = \frac{6FH}{Bt^2} \quad (1)$$

where B, H and t is the width, height and thickness of the steel plate, respectively. Based on the assumption that the section edge stress along the plate height is identical, the yielding force, F_y, of the TSD can be expressed as Eq. (2).

$$F_y = \frac{N\sigma_y Bt^2}{6H} \quad (2)$$

where σ_y is the yielding stress of the steel plate. The edge curvature of the plate section φ_y is determined using Eq. (3).