Engineering Structures 167 (2018) 518–532

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic design method analyses of an innovative steel damping bearing for railway bridges

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ARTICLE INFO

Keywords:
Steel damping bearing
Force-based design method
Displacement-based design method
Shaking table tests
Numerical analyses

ABSTRACT

The bearing sliding effect of the pot bearing and plastic deformation of a low-yield steel damper has been proven to be effective in mitigating the seismic response of railway bridges during earthquakes. However, both the sliding effect and plastic deformation require large bearing and pier dimensions to avoid unseating damage during earthquakes, leading to higher costs during construction of the railway bridge. On the basis of bearing sliding and energy dissipation, a novel steel damping bearing is developed by using "function separated design". The steel damping bearing is composed of a pot bearing to support the vertical loads and a series of low-yield steel dampers to bear the horizontal seismic loads. In this paper, both the force-based and displacement-based design methods for the steel damping bearing are analysed by using the equivalent linearization method. Then, a 1:7 scale two-span simply supported railway bridge model is tested on a shaking table under different ground motions to estimate the design method results for the steel damping bearing. Additionally, a bridge model with pot bearings is tested as a benchmark model. Finally, the prototype bridge is modelled by numerical analysis to evaluate the effectiveness of each design method. The experimental and numerical results reveal that both design methods can effectively simulate the response of the bridge model. Moreover, a comparison between the models with steel damping bearings and with pot bearings reveal that the steel damping bearing can greatly mitigate the pier forces and displacement with an acceptable displacement between the pier and girder.

1. Introduction

In the past three decades, seismic isolation devices, installed between the superstructure and the substructure, have been widely used to protect bridges in seismic areas [1,2]. These isolation devices can isolate the inertia forces transferring from the superstructure to the substructure to protect the bridge piers during earthquakes. A rubber bearing, which has been proven to provide a sufficient level of safety for these bridges [3–5], is the preferred bearing for the recent large-scale railway bridge construction in China. However, experiments conducted by Takaoka [6] show that these rubber bearings may undergo buckling under large shear deformation, possibly resulting in swaying movement of the superstructure when the horizontal deformation exceeds the bearing diameter. This swaying movement will lead to considerable destruction of the rail on the superstructure.

Recently, experimental and numerical studies [7,8] have been carried out, and it has been found that the sliding effect of a sliding bearing, instead of the shear deformation of a rubber bearing, can also provide seismic isolation for the substructure. Steelman et al. [9–11] conducted quasi-static experiments on a laminated elastomeric bearing with and without a polytetrafluorethylene (PTFE) plate and steel fixed bearings, and found that the bearing sliding can greatly isolate the seismic forces from the superstructure to the substructure, even for these kinds of non-seismic bearings. Their experiments also suggest that the bearing sliding will result in a large displacement of the bearing, and unseating damage can occur. Filipov et al. [8] analysed a three-span continuous bridge by considering the influence of the abutment and concluded that including abutments on both sides can greatly restrain the bearing displacement.

However, many bridge spans are presented along a long-distance simply supported railway bridge, resulting in a small effect of the abutment restraint. Li et al. [12] recently conducted shaking table tests of the sliding bearing with X-type steel dampers on the side of the bridge; the X-type steel dampers are used to mitigate the seismic response of the bearing. Their test results reveal that the steel dampers can mitigate the displacement of the bearing with a small increase in the pier moment. However, the X-type steel dampers are installed on the side of the bridge model, and only the lateral seismic responses can

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https://doi.org/10.1016/j.engstruct.2018.04.076
Received 15 January 2018; Received in revised form 20 April 2018; Accepted 21 April 2018
0141-0296/

be mitigated. Based on the studies of Meng [13], the X-type steel damper can be used only for highway bridges and is not suitable for railway bridges, as the large mass of the railway bridge girder will lead to considerably greater seismic forces than those in the highway bridge. Thus, the studies of Meng [13,14] recommend low-yield steel damping bars installed in parallel; both hysteretic experiments and numerical analyses have shown that steel damping bars have stable hysteretic behaviour and can greatly mitigate seismic responses. However, practical engineering of the Wei River railway bridge in Xi'an, China, shows that this type of steel damping bar usually requires large dimensions, e.g., 600–800 mm high, to produce large plastic deformations; large steel damping bars are difficult to install and replace because the height of the pot bearing with pinner is usually approximately 500 mm [15].

Based on the bearing structure proposed by Li [12], a novel steel damping bearing is developed; this steel damping bearing is composed of a pot bearing and low-yield steel damping bars and was proposed by Meng [13,14]. The basic concept of the bearing is "function separation" [13], which means that the pot bearing only supports the vertical loads from the superstructure and that the steel dampers bear the horizontal seismic forces. During earthquakes, the pot bearing will slide, and the steel dampers around the bearing will undergo plastic deformation to dissipate the energy and mitigate the seismic response. To decrease the dimensions of the steel damper without decreasing the plastic deformation, the steel dampers are connected in series, which allows the total bearing deformation to be twice the plastic deformation of steel dampers connected in parallel. Quasi-static experiments conducted by Li [16] show that the steel damping bearing with steel dampers in parallel destroyed at the displacement amplitude of 80 mm, while the bearing with steel dampers in series can complete the whole test of 200 mm displacement amplitude without failure. Numerical analyses also reveal that once some of steel dampers fracture during earthquakes, the redistribution of the seismic forces on the other steel dampers will lead to the failure of the bearing with steel dampers in parallel, while this will not happen in the bearing with steel dampers in series [17].

Additionally, in the research conducted by Li et al. [12], for some cases with X-type steel dampers, the pier strains also exceeded the yield strains, indicating that the steel damper did not have an optimal design. The numerical analyses conducted by Providakis [18] show that the suitable design of a steel damper can reduce the relative displacement between the pier and girder without significantly increasing the seismic response. In traditional seismic design, the force-based design (FBD) method is recommended by most current standards [19,20]. However, the FBD method cannot sufficiently provide the appropriate means for implementing concepts of performance-based earthquake engineering design [21]. Performance levels should be described in terms of displacement, as damage more accurately correlates to displacements than forces due to the plastic behaviour of the materials. One such approach is the displacement-based design (DBD) method, proposed by Priestley [22]. The major goal of the DBD method is to obtain a structure that will reach a target displacement when subject to earthquakes consistent with a given displacement response spectrum [23].

In this study, the initial stiffness of the steel damping bearing is first calculated by using the stiffness of the steel dampers and the friction coefficient of the bearing. Then, both the FBD and DBD methods based on the selected equivalent linearization method are developed for the steel damping bearing. A 1:7 scale two-span simply supported railway bridge model with steel damping bearings is tested on a shaking table under different ground motions to evaluate the effectiveness of both design methods, and the same bridge model with pot bearings is tested as a benchmark model. The peak ground accelerations (PGAs) of the ground motions are varied from 0.3 g to 0.75 g with an increment of 0.15 g, and three ground motions are selected for each PGA. For convenient installation of the experiments, the mechanical parameters of the steel damping bearing are consistent for different ground motions and various PGAs. The bearing displacement, pier displacement and

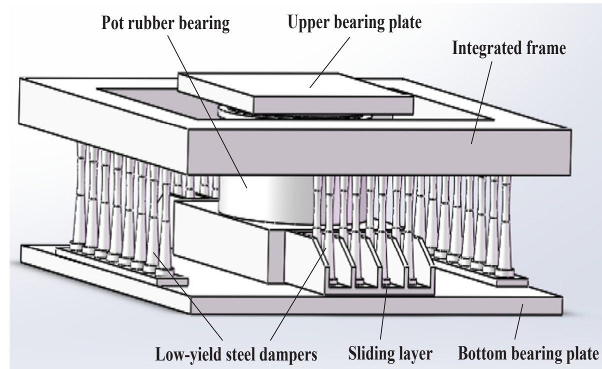

Fig. 1. Compositions of the steel damping bearing.

pier force are calculated with both design methods and then compared with the test results. Furthermore, a series of numerical analyses of the prototype bridge are conducted to estimate the design methods. The mechanical parameters of the steel damping bearing are first calculated by using the design methods. These parameters are then applied in the numerical analyses to calculate the pier displacement, bearing displacement and pier force. The same ground motions and PGAs are used in the numerical analyses, and only the longitudinal seismic responses are analysed in this paper.

2. The steel damping bearing

2.1. Construction of the steel damping bearing

Fig. 1 presents the configuration of the steel damping bearing, while Fig. 2 shows a detailed drawing of the bearing. The bearing mainly contains six parts, as shown in Fig. 1: upper bearing plate, integrated framework, pot bearing, low-yield steel dampers, sliding layer and bottom bearing plate. The proposed bearing is a combination of seismic isolator and energy dissipation devices. The top surface elevation of the upper bearing plate is higher than that of the integrated frame; thus, the vertical loads from the superstructures are transferred by the pot bearing. The upper and bottom bearing plates are anchored in the girder and the pier, respectively. The lateral stiffness requirements of the bridge in service conditions can be satisfied by using a steel damping bearing, as verified by the studies of Meng [14]. Additionally, shear pins (Fig. 2(b) and (c)) are installed between the sliding layer and the bottom bearing plate to resist large longitudinal service loads such as vehicle braking loads. Under strong ground motions, the shear pins will firstly break off due to the seismic force, and then the steel dampers will undergo plastic deformation. In Fig. 2(c), the connecting bolts used to connect the pot bearing and the sliding layer are also shown in detail.

During earthquakes, after the shear pins break off, the upper bearing plate will undergo movement, leading the sliding layer slide relative to the bottom bearing plate. An ultrahigh molecular weight polyethylene (UHMWPE) material is placed between the sliding layer and the bottom bearing plate; this kind of material has been confirmed to be stable after many cycles under atmospheric conditions. Then, the steel dampers installed on the sliding layer will undergo bending deformation. Because the steel dampers anchored on the bottom bearing plate are connected to the steel dampers installed on the sliding layer by the integrated frame, the movement of the sliding layer will also induce plastic deformation of the steel dampers on the bottom plate. The "series connection" is realized by the sliding layer and the integrated frame, which can amplify the bearing displacement and take full advantage of the energy dissipating capability of the steel dampers.

Because of the low friction coefficient, approximately no shear deformation of the bearing occurs during earthquakes, and the movement of the pot bearing can be considered an approximately rigid body