Journal of Constructional Steel Research 101 (2014) 83–95

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Development of an energy dissipation restrainer for bridges using a steel shear panel

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ARTICLE INFO

Article history:
Received 1 October 2013
Accepted 31 March 2014
Available online 3 June 2014

Keywords:
Bridge
Restrainer
Energy dissipation capacity
Finite element model
Parameter fitting

ABSTRACT

Restrainers, along with isolation bearings, are often installed in bridges to avoid upper girders falling off their piers during large earthquakes. In this study, a novel energy dissipation restrainer was developed. The energy dissipation restrainer remains elastic and provides a reaction force to restrain the displacement of the girder during small earthquakes, maintaining the functionality of the bridges. When large earthquakes occur, the restrainer can yield and dissipate energy, thus reducing the deformation between the superstructures and piers, and protecting the piers from server damages. To verify the performance of the restrainer, five specimens were designed and subjected to physical loading tests. The test results suggest that when appropriately designed, the restrainer has satisfactory deformation and energy dissipation capacities. The thickness of the side flange and width of the energy dissipation plate have significant effects on its performance. Because the number of physical tests was limited, finite element models were built using the general finite element program ABAQUS to supplement the results, and a parametric study focusing on the effects of the side flange thickness and restrainer width was conducted. Based on the test and analysis results, a formula for estimating the restrainer strength was derived.

1. Introduction

The unseating of superstructures is the most common failure mode for bridges when subjected to strong ground motion [1–3]. To prevent superstructures from dropping off piers, restrainers with adequate strength are usually installed in bridges to restrain the displacement of the superstructure [4]. Post-earthquake investigations suggest that bridges equipped with restrainers sustain only minor damage in earthquakes and there is no disruption to traffic [5,6].

Investigators have developed many types of restrainers, e.g., steel cables, concrete walls, steel plates, and shape memory alloy (SMA) devices. Numerical models of bridges with restrainers have been built and their response during earthquakes was analyzed [7,8]. The results obtained from the studies indicate that restrainers can effectively prevent the unseating of the superstructure and reduce the damage to the bridge.

There are mainly three types of restrainers, namely rigid, yielding, and SMA restrainers. The rigid restrainers, which are commonly made of concrete walls, are designed to completely restrain the displacement of the superstructure of the bridge. Bridges with rigid restrainers have inadequate energy dissipation capacity; therefore, the acceleration of the superstructures and the shear of the piers in those bridges are greater than those of bridges with yielding and SMA restrainers during large earthquakes [9]. Moreover, rigid restrainers do not have good deformation capacity, leading to a brittle failure when large earthquakes occur, which requires difficult and lengthy repairs [5].

Much research on SMA restrainers has been carried out [10–13]. SMA restrainers can reduce the residual displacement of the superstructure and can dissipate large amounts of energy to reduce damage to the bridge. However, the properties of SMA materials are not necessarily stable when they sustain cyclic thermal or mechanical loading [14,15]. In addition, the costs of restrainers made of SMA are much higher than those made of most common metals.

Yielding restrainers, usually made of steel, have stable mechanical performance and are cost-effective. The response of bridges with yielding restrainers is very close to that of bridges with SMA restrainers [9]. Yielding restrainers made of reinforced concrete and steel have also been proposed [16,17]. These studies showed that properly designed yielding restrainers have good and stable mechanical properties and are suitable for engineering applications.

In this study, a novel energy dissipation restrainer for a bridge is proposed. The energy dissipation restrainer remains elastic and provides a

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http://dx.doi.org/10.1016/j.jcsr.2014.03.009
0143-974X/

reaction force to restrain the displacement of the girder during small earthquakes, maintaining the functionality of the bridges. When large earthquakes occur, the restrainer can yield and dissipate energy, thus reducing the deformation between the superstructures and piers, and protecting the piers from server damages. To achieve the two-stage performance goals, the strength and deformation capacity of the restrainer are key parameters. In this paper the structure of the novel restrainer is presented first. Five specimens were designed and tested to investigate the mechanical properties of the restrainer. The test results indicate that an appropriately designed restrainer performs well mechanically. Because the number of specimens in our tests was limited, finite element (FE) analyses were carried out to supplement the physical tests. Finally, based on the tests and analysis results, a design formula for estimating the ultimate strength of the restrainer is proposed.

2. Structure of the restrainer

The restrainers are commonly installed with the isolation bearings between the upper girders and lower piers. As shown in Fig. 1, the restrainer consists of an energy dissipation plate and two horizontal locking blocks. The energy dissipation plate is fixed on the lower piers while the horizontal locking blocks are bolted to the bottom of the girder by high-strength bolts. Note that following the installation (Fig. 1, left) the restrainer only takes effect along the transverse direction of the bridge and does not provide resistance in both vertical and longitudinal directions. This is beneficial for easy installation and to guarantee the performance of the restrainer. The restrainer can also be used in the longitudinal direction by changing the installation angle (Fig. 1, right). When a superstructure is displaced relative to the piers, the horizontal locking blocks will force the energy dissipation plate to deform. During a small earthquake the energy dissipation plate remains elastic and provides reaction forces to restrain the displacement of the upper girder. When a large earthquake occurs it yields and dissipates the energy, thus reducing the responses of the bridge. The energy dissipation plate can be easily replaced if damaged, so the bridge can be quickly repaired after an earthquake. Small gaps, which is commonly about 2 mm, are set between the energy dissipation plate and the horizontal locking blocks for the convenience of installation and replacement. The horizontal locking blocks are designed to be rigid so that the deformation is concentrated in the energy dissipation plates; therefore, this study mainly focuses on the performance of these plates.

The details of the restrainer are shown in Fig. 2. The dimensions of the horizontal locking block are shown in the lower right corner of Fig. 2. A semi-circular piece of steel is welded onto the connection plate to accurately determine the height of the contact point. To design the horizontal locking block we adopt a simple formula

$$f_y A > \lambda F_u \tag{1}$$

where f_y is the yield strength of the material and A is the area of the cross-section of the horizontal locking block. F_u is the total reaction force of the energy dissipation plate and λ is a conservative factor which should be larger than 1 to guarantee the horizontal locking block remaining elastic during an earthquake. We assume the maximum F_u to be 600 kN and f_y is set as 310 MPa. Setting $\lambda = 4$, A should be larger than 5655 mm^2. In Fig. 2, $A = 10{,}500$ mm^2, which meets the requirement of Eq. (1).

The web area of the dissipation plate is the main area for energy dissipation, outlined in bold in Fig. 2. The width and height of the web (w and h, respectively) are the main parameters relating to energy dissipation. The top flange and the side flange are welded to the web. A stiffener is added to prevent out-of-plane buckling of the web. Fillet welding, 6 mm thick, is used to weld the stiffener and flanges to the web. The energy dissipation restrainer works in a manner similar to that of shear panels, which are commonly used as steel dampers in building structures [18–20]. However, the vertical free mechanism and force concentration at the contacts between the energy dissipation plate and the horizontal locking blocks require the energy dissipation plate to have a different structure. To this end, we carried out physical tests to investigate its optimal design.

3. Testing procedure

The width of the energy dissipation plate w, the thickness of the top flange t, and the thickness of the side flange b were the main parameters in the tests. Five specimens were designed as shown in Table. 1. S1 is the standard specimen in the study. The stiffeners of S1 were designed by following the requirements of a steel shear panel damper. S2 has thin side-flanges that are 6 mm thick. S3 has a thinner top flange which is 10 mm thick. In S4 the width of the web was reduced to 150 mm, and. S5 has additional horizontal stiffeners. The web plates of all the specimens are 300 mm high and 6 mm thick. The stiffeners are 100 mm wide, and the side flanges are 200 mm wide.

The loading setup, consisting of an actuator and a loading frame, is shown in Fig. 3. The loading frame was fixed to the ground with anchor bolts. The horizontal locking blocks and the energy dissipation plate were connected to the upper loading frame and the lower base using high-strength bolts. The horizontal locking blocks, which are in contact

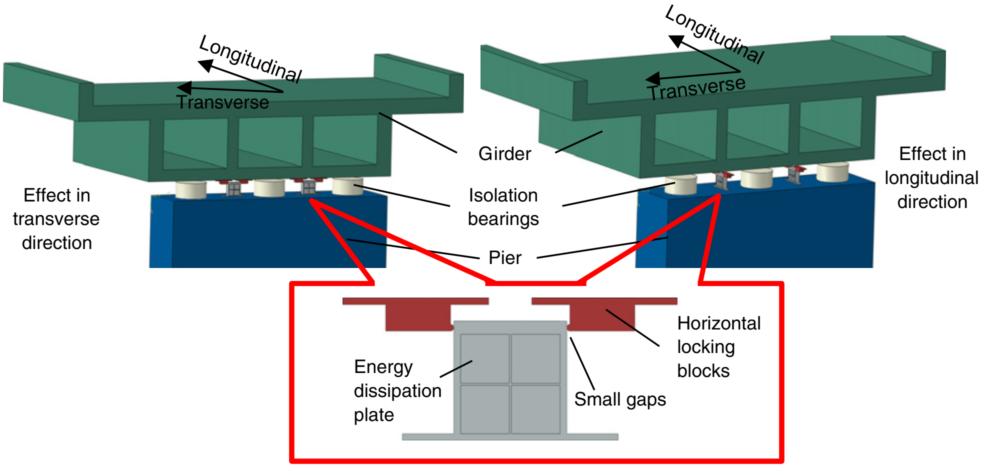

Fig. 1. Installation diagram of the restrainer.