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Experimental investigation on seismic retrofit of gravity railway bridge pier with CFRP and steel materials

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HIGHLIGHTS

- Seismic retrofit of gravity bridge pier with low reinforcement ratio is investigated.
- Retrofitting techniques by the use of CFRP wrapping and bonded-steel are provided.
- Bottom-anchoring system with planted steel bars and new concrete jacket are presented.
- Seismic response of retrofitted piers is studied by quasi-static test of scaled model.

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ABSTRACT

Seismic retrofit is a cost-effective sustainable approach to strengthen older deficient bridges or repair damaged bridges, in seismic zones. The steel and CFRP materials could be used to retrofit gravity railway bridge pier with low longitudinal steel ratio, in China. Quasi-static tests for 1/8-scale model piers of a widely-used type of gravity railway bridge pier applied in quake-prone region of China were performed to evaluate the seismic performance before and after retrofitting. It was found that the gravity bridge pier with low longitudinal steel ratio was vulnerable at the pier-footing region and exhibited inadequate ductility under lateral cyclic loading. After retrofitting by the CFRP wrapping and bonded-steel, the load-carrying capacity of the bridge pier was enhanced by more than 100%. Moreover, the anchorage system with the planted steel bar and new concrete jacket on the column, above the footing, can relocate the fracture region of the retrofitted pier. The hysteretic behaviors indicated that the energy dissipation of retrofitted piers can be improved due to the deformation or failure of the wrapped-CFRP and bonded-steel during earthquake. Therefore, it can be concluded that seismic retrofitting techniques by the use of CFRP and steel materials are effective for the gravity railway bridge pier with low longitudinal steel ratio in China.

1. Introduction

Many railway bridges in China have been built in regions of high seismic activity, and which constitute a significant portion of railway infrastructures [1,2]. It is worth noting that strong earthquakes frequently occur in China, especially in recent decades, e.g. Wenchuan earthquake in 2008 [3], Yushu earthquake in 2010 [4], Jiuzhaigou earthquake in 2017 [5], etc. Bridges are often considered the most critical link in the railway network, the damage or collapse of bridges during an earthquake can cause a long term disruption to the transportation system [6,7]. It is time-consuming and costly to replace the severely damaged bridge by a newly designed one after an earthquake. However, an appropriate retrofitting technique is often more efficient and economical than replacement. Seismic retrofit is the practice of modifying the older deficient bridges or repairing the damaged bridges to improve their seismic performance in subsequent earthquakes [8–10].

Lessons learned from recent earthquakes have shown that the pier is one of the vulnerable components for bridges during earthquakes [11–14]. Generally, retrofitting techniques for enhancing the seismic performance of the bridge are based on an external jacketing or wrapping of the bridge pier or part of it, using different materials, such as steel plates, thin layers of concrete, carbon fiber reinforced polymer (CFRP), and other new composite materials [10,15–18]. The concrete jacket provides lateral confinement and improves the bending and shear capacity of the original pier, while the retrofitting efficiency is reduced with the pier height increase,

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showing important benefits in bridges with short length piers [19], so the application will be limited when the pier height increases. Another jacket, the steel plate, has been shown to be very effective in enhancing the flexural and shear performance of deficient bridge columns, which was widely used in the California (US) and Japan [20–22]. Some reinforced concrete piers strengthened by using the steel jacketing suffered few damage during the 1995 South Hyogo earthquake in Japan [22]. Aboutaha, et al. [23] investigated several types of steel jackets, including rectangular solid steel jackets and partial steel jackets, indicated that a thin rectangular steel jacket can be a highly effective retrofit measure for reinforced concrete columns with inadequate shear resistance. Other experimental research results showed that the retrofit of various types of steel jackets resulted in enhancing of the column ductility and inhibits bond failures in lap splices of longitudinal steel [24,25]. Although steel jacketing were widely used in seismic retrofitting, other alternative materials, like the carbon fiber-reinforced polymer (CFRP) and other fiber composites, which have light weight and high strength, are increasingly applied for retrofitting. The FRP composite jacketing is highly effective in confining the core concrete and preventing the longitudinal reinforcement bars from buckling under cyclic loading [26]. Yeh and Mo [27] found that CFRP sheets can effectively improve both the ductility factor and the shear capacity of hollow bridge piers. The post-earthquake quick recoverability is also important for the retrofitting techniques of bridges [28], rapidly repaired piers would greatly facilitate the rescue process. Sun, et al. [29] suggested that the repair technique using the early-strength concrete jacket confined by CFRP sheets can be an optimal method for the rapid repair of severely earthquake-damaged circular bridge piers with flexural failure mode.

As discussed above, the seismic retrofitting techniques for bridges have been well developed in US and Japan. These existing researches mainly focused on highway bridges with flexible piers (i.e. multi-slender column, hollow pier etc.) or short columns with transverse reinforcement [30]. But in China, the bridge pier featured with large-dimension and solid section, which is defined as the gravity pier, has been widely used in existing railway bridges. Moreover, large numbers of older gravity railway bridge piers were constructed by reinforced concrete with low longitudinal steel ratio (lower than 0.5%), in seismic regions. However, the seismic retrofitting techniques of these gravity piers have not been paid much attention by researchers for a long time. In this study, seismic retrofitting techniques by using the bonded-steel and CFRP wrapping were provided for gravity railway bridge piers with low longitudinal steel ratio. The static and seismic performances of the gravity bridge pier were evaluated by quasi-static testing with three 1/8-scale model specimen.

2. Experimental program

2.1. Scaled model design

The quasi-static testing in this study are designed to obtain static and seismic performance of gravity railway bridge piers which have been widely used in regions of high seismicity in China [31]. The gravity bridge pier in standard drawing for railway construction of China is selected as the prototype, which can represent a widely-used type of railway bridge piers in seismic regions of China. The selected prototype pier is 20 m-height, and has a rectangular cross section with a size of 513 × 357 cm. The prototype pier has 180 longitudinal steel bars with a diameter of 16 mm evenly distributed around the column, and the longitudinal steel ratio is about 0.2%. The stirrup diameter and spacing of the prototype pier are 16 mm and 100 mm, respectively, and the stirrup ratio is about 0.2%. In this study, three scaled model piers (M1-M3) were constructed, which were designed based on a 1/8 scale of the prototype pier. The height of the model pier was 2.5 m, and the size of the cross section was 64 × 45 cm, a bearing platform with a cross section size of 100 × 220 cm was designed at the bottom of the pier. The hook for lifting and high-tensile steel bars for lateral loading were pre-embedded at the top region of the scaled model pier, as shown in Fig. 1.

In order to correctly scale down the prototype bridge pier, coefficients accounting for similarity in material properties, geometry, loading properties are calculated based on Buckingham π Theory [32,33]. The basic similarity coefficient of pier stress is 1.0, and

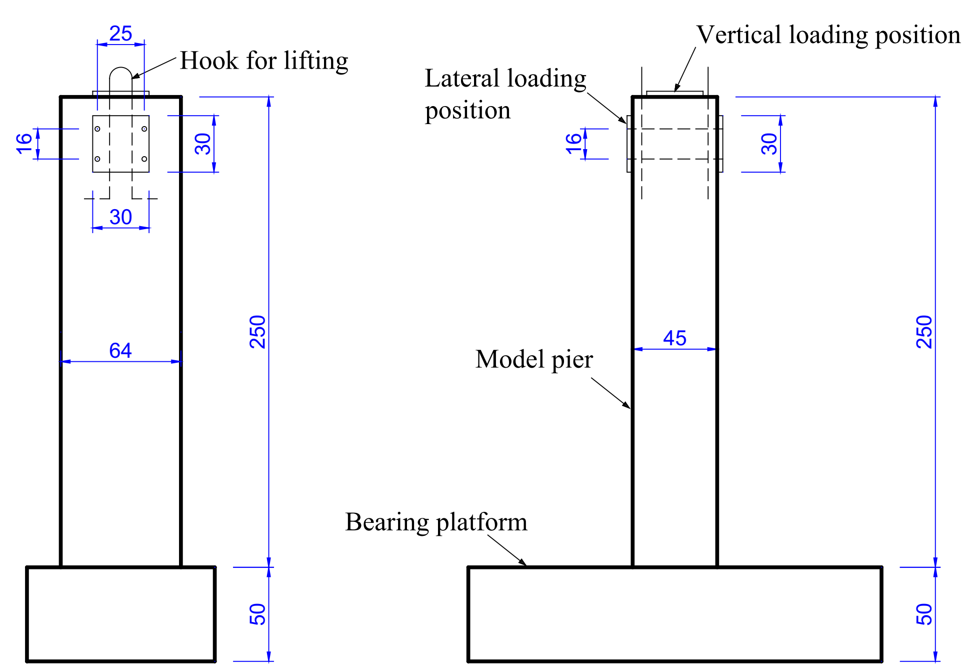

Fig. 1. Size and shape details of the scaled model pier (unit: cm).