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Investigation and verification on seismic behavior of precast concrete frame piers used in real bridge structures: Experimental and numerical study

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In this study, quasi-static cyclic test was conducted for three 1/3-scale specimens of different precast concrete frame pier structure systems of an urban viaduct in Shanghai, China. Various connection deployment strategies were utilized for the specimens, in order to verify these precast concrete frame piers used in the real structure. Two of the specimens were of the same cap beam design, while the third one was with tie beam. The two frame piers with cap beam had the same column-footing connection (grouted splice sleeve coupler), but the column-cap connections were grouted splice sleeve coupler and grouted corrugated duct connection, respectively. The frame pier with cast-in-place tie beam, however, only kept the grouted splice sleeve coupler for column-footing connection. The cyclic test results showed similar seismic behavior of the two specimens with cap beam, whereas the specimen with tie beam exhibited less energy dissipation capacity. This indicated that the seismic performance differences among the specimens are mainly caused by different structure systems, and the two types of the connections behave similarly with little damage. Finite element models that were optimized by considering joint region behavior and bond-slip phenomena showed good agreement with the test results.

1. Introduction

Bridge design and construction have experienced innovations and advancements in recent years, which lower overall cost, simplify construction process, and save time [1]. Bridge columns, cap beams, and bridge girders can be prefabricated in factories or near construction sites. These components are then assembled on-site using different types of connections for accelerated construction. However, connections are usually applied to critical structural locations (e.g. column-cap and column-footing joints), where plastic hinges are likely to form under strong earthquakes. Thus, studies on the bridge structures with moment-resisting connections need to be taken special care of in moderate-to-high seismic zones.

Five different types of connections were studied and used in real applications [2]. Socket connection, applied to column-footing joints, was recently utilized for highway bridges, and studies showed acceptable seismic performance [3,4]. The second type is pocket connection, and its seismic performance was also reported to be comparable to cast-in-place (CIP) structures [5]. Prestressing tendon is the third type of connection, which is commonly used in precast segmental bridge columns. Seismic behavior of these precast segmental posttensioned bridge columns was investigated experimentally, and test results showed that the segmental columns exhibit good drift capacity and ductility, and energy dissipation capability can be ensured by using energy dissipation bars [6,7]. The remaining two connection types are grouted corrugated duct connection (GCDC) and bar coupler connection, and these connections are studied in this paper. GCDC was originally developed for column-cap connections [8,9], but study of column-footing connection using GCDC was also conducted with promising results for construction [10], and good ductile performance was observed when compared with CIP systems. The bar coupler connection includes several types of proprietary mechanical bar couplers or splicing devices, one of which is grouted splice sleeve coupler (GSSC). GSSC was also studied for applications in seismic zones, including the utilization of multiple reinforcing bars, high-strength grout, and cast iron sleeve [2,11–13]. The experiments showed that specimens using GSSC and corresponding CIP structure retained equivalent strength capacity, but displacement capacity was found to be lower [14–17]. Further research studies revealed that displacement capacity can be improved by allowing debonding of reinforcing bars outside the GSSC [18]. Comparison of three specimens with various GSSC embedding locations also confirmed results of previous studies [19].

Numerical simulation was conducted to obtain better knowledge on the overall performance of the structures and connections. A two

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dimensional (2-D) finite element model (FEM) was developed to simulate the precast bridge column using GCDC by modifying the elastic modulus of the reinforcing bar to consider bond-slip effect at the column-footing area [10]. Another two types of bond-slip models were proposed to explore the bond response of stainless energy dissipation bars installed in GCDC [20]. GSSC was modeled in 2-D with a nonlinear rotational spring to simulate the bond-slip effects [18,21,22].

Studies regarding the different types of connections are mainly focused on single-column piers, and those of dual-column frame piers are lacking. Only a few quasi-static cyclic tests were performed for precast dual-column frame piers with the combination of GCDC, socket and pocket connections [23,24]. Test results showed that the precast frame piers achieved good strength and ductility in comparison with CIP construction. A multi-shaking table test of a quarter-scale bridge system of two-span, three dual-column frame piers was conducted with socket and hybrid-bar-socket connections, and the maximum displacement of the precast piers was comparable with the conventional bridge [25]. State-of-practice of precast pier cap systems, including GCDC, GSSC and pocket connections, was reported by researchers and it was concluded that seismic behavior of connections was critical to system ductility [26].

This paper presents experimental and numerical study of three 1/3-scale specimens of precast bridge substructures (dual-column frame pier) that are assembled with different connections (GCDC and GSSC) under lateral quasi-static cyclic load. The specimens are based on the precast frame piers that are utilized in urban viaducts of highway S6 in Shanghai, China. The viaducts also retain the precast bridge decks, and the frame piers are commonly used as a substructure for these decks, which led to the choice of such structure system. Since it is permitted by the load capacity of the cranes, the columns can remain the integrity without being divided into several segments, which also facilitates the construction process. The two types of connections are proven by the contractors to be more convenient than others in terms of construction. For example, it avoids the post-tensioning procedure, if the precast hollow section piers are used. Moreover, the deployment strategies of these connections of the frame piers (GSSC at both column ends, and combined GSSC and GCDC at each end) have never been used and studied, and therefore the seismic behavior of these frame piers is unknown and needed to be investigated and verified.

Study on seismic behavior of six precast single-column piers with different connection details was also conducted by the present authors [27], including GSSC, GCDC and posttensioned connections. The columns with GSSC and GCDC were designed the same as those of frame pier specimens studied in this paper, and their seismic performances were compared with the CIP benchmark. It was concluded that these columns with GSSC and GCDC were emulative of CIP reinforced concrete columns if high-strength grout was used. Therefore, the seismic behavior of precast bridge frame piers is investigated without a CIP reference in this study. Two of the specimens are with cap beams and share exactly the same design except for the connections, while the third one uses CIP tie beam design. The test results were compared to further understand the seismic behavior of the frame piers. 2-D FEMs were also developed with different approaches to optimize the accuracy of simulation. The bond-slip phenomena were simulated by considering 6% inactive length of the skin reinforcements at both ends of the columns, and the beam-column joint region behavior unique to frame piers was also considered.

2. Test setup

2.1. Specimens

The urban viaducts of highway S6 in Shanghai possess a total length of 11.8 km. It provides a crucial passage and eases the pressure of the city transportation. These continuous bridges that were constructed along the highway are 30 m long for each span (Fig. 1). In order to accommodate the traffic and design requirement, all the three precast frame pier designs of the tested specimens are used. The bridges with box-girders are more suitable for the piers with tie beam design, while the ones with T-girders are better supported with cap beam design. Moreover, GCDCs require long anchoring length (> 25 times the rebar diameter), while GSSC needs shorter length (8–10 times the rebar diameter). The cap beams at different locations do not maintain the same height, and GSSC is thus used where the cap beam height cannot meet the anchoring requirement of GCDC, while GCDC is implemented for those with enough height in terms of economic efficiency. In addition, an ongoing study of the durability of these connections and designs also requires all the bridge pier types to be constructed and monitored to serve this purpose. These three types of the precast frame pier specimens are tested for verification purposes, and each one has a unique connection deployment, but they are with the same column dimension and mild reinforcement arrangement.

The concrete material used is C40, and its nominal uniaxial compressive strength and modulus of elasticity are 26.8 MPa and 3.25×10^4 MPa, respectively. To determine actual concrete strength, nine 150 mm concrete cubes made from the same concrete sample are modeled and standard-cured for 28 days. The average compressive strength of the nine cubes is 33.5 MPa, and the modulus of elasticity is 3.3×10^4 MPa. For mild reinforcement, hot-rolled plain bar with nominal yield strength of 235 MPa (HPB235) and hot-rolled ribbed bar with nominal yield strengths of 335 MPa and 400 MPa (HRB335 and HRB400) are used. Nominal moduli of elasticity are 2.1×10^5 MPa for HPB235 and 2.0×10^5 MPa for HRB335 and HRB400. Based on coupon tests of the three specimens from each type of steel, the average measured yield strengths of HPB235, HRB335 and HRB400 are 243 MPa, 390 MPa and 432 MPa, and the averaged ultimate strengths are 404 MPa, 499 MPa and 601 MPa. High-strength grout is used for the connections, and nine 70 mm cubes are modeled and standard-cured with an average 28-day compressive strength of 104 MPa.

The columns in all three specimens are 3050 mm tall with the rectangular cross-section of 500 mm × 530 mm (Fig. 2). In order to keep the same loading height, the footing of specimen #3 is raised from 600 mm to 750 mm to compensate the height decrease due to the tie beam design. Detailed reinforcement arrangements for columns are shown in Fig. 3(a)–(c). The longitudinal reinforcements consist of 20 mm-diameter HRB400s and 8 mm-diameter HPB235s that is referred to as skin reinforcement for crack prevention. The hoops are 8 mm-diameter HPB235s and the ties are 6 mm-diameter HPB235s, and both are spaced at 50 mm. For locations where GSSC and GCDC are embedded, stirrups and ties are all 8 mm-diameter HPB235s spaced at 45 mm. Reinforcement arrangement for the tie beam is shown in Fig. 3(d). The longitudinal reinforcements consist of 10 mm- and 12 mm-diameter HRB335s. The hoops and ties are 8 mm- and 6 mm-diameter HPB235s with a clear spacing of 60 mm.

GSSC is a hollow steel bar coupler that connects the rebars from each component, while GCDC is a flexible corrugated metal tube that provides the guidance for the protruding rebar of one component to be inserted into another component. In terms of the placement of connections, GSSCs are embedded in the footing and cap beam of specimen #2, while GSSCs are replaced by GCDCs in the cap beam for specimen #1. Specimen #3, however, only has GSSC placed inside the lower ends of the columns, and no connections are used at the upper ends due to the CIP tie beam. The lengths of GSSCs and GCDCs are 360 mm and 700 mm, and the nominal diameters are 66.5 mm and 40 mm, respectively. The details of the GSSC and GCDC used in the specimens are shown in Fig. 4.

The fabrication processes of specimens #1 and #2 are similar, and the only difference between the two is the protruding length of the 20 mm-diameter longitudinal rebars (175 mm for GSSC and 680 mm for GCDC). The precast segments include pier cap, column, and footing, as shown in Fig. 5(a)–(c). After the completion of concrete curing, the columns of each specimen are mounted on the footing by inserting the