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Experimental testing and modeling of precast segmental bridge columns with hybrid normal- and high-strength steel rebars

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HIGHLIGHTS

- A novel PSBC reinforced with hybrid normal- and high-strength rebars was proposed.
- Cyclic tests on large-scale hybrid reinforced PSBCs were conducted.
- Hybrid reinforcement was very effective in improving the post-yield stiffness, self-centering capability and ductility.
- A new and efficient fiber-based FE modeling method was developed and validated.

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ABSTRACT

Precast segmental bridge columns (PSBCs) have significant advantages, including faster construction speed and lower environmental impacts, over cast-in-place bridge columns. Traditional PSBCs usually employ normal-strength steel rebars as longitudinal reinforcement. Hence, it is named the NSR-PSBC herein. In this paper, a novel PSBC, named hybrid-reinforced PSBC (HR-PSBC), is developed. The HR-PSBC utilizes hybrid normal- and high-strength steel rebars to improve the seismic response of PSBCs. The main contributions of this study include: (1) large-scale cyclic tests were conducted to compare the seismic performance of the HR-PSBC with the NSR-PSBC; and (2) a novel and computationally efficient finite element model for the HR-PSBC was developed. The test results demonstrated that the hybrid reinforcement employed in the HR-PSBC was very effective in improving the post-yield stiffness, self-centering capacity, ductility and load-carrying capacity of the bridge column. These test results were further used to verify the accuracy of the proposed finite element model. It was found that the numerical model was able to provide satisfactory predictions of both global and localized responses of the PSBCs. Based on the results presented in this paper, it is concluded that the HR-PSBC can be a promising alternative to traditional NSR-PSBCs and cast-in-place bridge columns, and the proposed numerical modeling method can be a suitable tool for design-oriented studies of the NSR- and HR-PSBCs.

1. Introduction

With rapid population growth worldwide, new bridges are being constructed at an unprecedented speed to connect regional cities and regions within a city. In addition, numerous existing bridges need to be replaced or rehabilitated due to aging [1]. To minimize the impacts on the traffic and environment caused by bridge construction, precast segmental bridge columns (PSBCs) have been developed. This type of bridge column is segmentally prefabricated off-site and sequentially assembled on-site with post-tensioned tendons. PSBC offers many inherent advantages over conventional cast-in-place bridge columns, which include higher construction speed, reduced environmental impact and increased site safety [2].

During the past decade, extensive research has been devoted to experimental studies on the seismic performance of the PSBCs. Early on, Wang et al. [3] explored the effectiveness of utilizing

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normal-strength steel rebars across the segment joints of PSBCs. Such PSBC is referred to as a normal-strength steel reinforced PSBC (NSR-PSBC) in this study. Cyclic test results of four specimens indicated that the lateral load-carrying ability and energy dissipation capacity of the column were significantly improved by these bonded rebars. Ou et al. [4] further conducted cyclic tests on three NSR-PSBC specimens to explore feasible methods of preventing the rupture of longitudinal rebars under repetitive loading. To better understand the seismic behavior of the NSR-PSBCs, cyclic and shake-table tests were carried out by many other researchers [5–11]. These studies provide a wealth of information regarding the influences of such factors as the steel reinforcement ratio, prestressing force level, connection types between segments, on the nonlinear behavior of NSR-PSBCs. However, most of the past experimental research focused on verifying if certain strategies were beneficial in mitigating the maximum seismic responses of PSBCs, while few studies paid attention to improving the self-centering capability of the PSBC. As pointed out by Shrestha and Hao [12], reinforced concrete (RC) bridge columns that sustained large residual drifts after earthquakes will be unserviceable or unsafe, thereby causing serious problems in post-disaster rescue and evacuation. Furthermore, the inclined bridge columns are very difficult to be straightened and might consequently require demolition and reconstruction [13,14]. It is, therefore, important to improve the seismic performance of the PSBC with special attention paid to the column self-centering capability.

Some researchers have also devoted to developing finite element (FE) models of the PSBCs in the last decade. Kwan and Billington [15] proposed a 2D continuum-based FE model of the PSBC, in which the segment joint was not modeled. Ou et al. [16] further built a 3D micro-scale FE model which employed brick and truss elements to simulate the concrete segment and the steel reinforcement, respectively. Similar numerical models were also presented in the studies by Wang et al. [3], ElGawady and Dawood [17], Dawood et al. [18], Nikbakht et al. [19] and Li et al. [20]. These studies provided detailed descriptions of the monotonic behavior of PSBCs and demonstrated that the micro-scale FE models had good accuracy to simulate the local effects, including the stress concentrations due to segment joint opening behavior. However, these micro-scale models are not satisfactory for design-oriented parametric studies of bridge columns or numerical analyses of entire bridges, due principally to the great demand on computational resources [21]. Nevertheless, valuable research has been carried out by Bu et al. [22], in which a 2D macro-scale model of the PSBC using beam-column elements was developed. Research results showed that with regard to the design purpose, the macro-scale model is more efficient than the 2D and 3D micro-scale FE models. The segment joint of the PSBC was not explicitly simulated in the macro-scale FE model [22], which consequently can not reflect the distinctive features of the PSBC compared to the monolithic RC column.

According to these studies, two major research gaps regarding the PSBC have been identified as follows: (1) existing work aiming at reducing both maximum seismic responses and post-earthquake residual drifts of PSBCs is still limited; and (2) there are few FE models applicable for design-oriented parametric studies of the PSBCs, which involves a great amount of computation of the cyclic and earthquake responses. In this study, a novel PSBC which utilize hybrid normal- and high-strength steel rebars, named hybrid-reinforced PSBC (HR-PSBC), is proposed. The normal-strength steel reinforcement is primarily employed to dissipate the energy imparted by the earthquake, while the high-strength rebar is mainly utilized to improve the post-yield stiffness of the PSBC. Previous research by Sakai and Mahin [23] and Fahmy et al. [24] has demonstrated that RC bridge columns with higher post-yield stiffnesses can possess better performance with smaller peak displacements and residual drifts under seismic excitations. In other words, the hybrid reinforcement is expected to improve the seismic performance and the self-centering capability of the PSBC system.

The major objectives of the research presented herein are to: (1) experimentally verify the design concept of the HR-PSBC by comparing its seismic behavior to the conventional NSR-PSBCs with normal-strength rebars only; (2) investigate the effects of the gravity load on the seismic performance of the HR-PSBCs; and (3) develop a new fiber-based FE model of the HR-PSBC which is computationally efficient and can be adopted as a suitable tool for further design-oriented studies. To this end, three large-scale PSBC specimens with heights of 4.2 m and cross-sections of $0.6\ \text{m} \times 0.4\ \text{m}$ were cyclically tested. After that, a 2D macro-scale FE model was developed by using the Open System for Earthquake Engineering Simulation (OpenSees) software package [25]. The accuracy of the developed numerical model was further validated using the tested data.

2. Experimental program

2.1. Specimen design

Three large-scale PSBC specimens were designed and tested under combined lateral displacement and axial load. All the specimens were nominally identical in geometry. As illustrated in Fig. 1(a), the height of the specimen was 4.2 m and consisted of one rigid foundation, six column segments and one loading stub. The height and the cross-section of the column segment were 500 mm and 400 mm $\times$ 600 mm, respectively. Lateral displacement was imposed by a horizontal MTS actuator along the weak axis of the bridge column and at a height of 3200 mm above the foundation. As a result, the section depth h and the shear span L of the column were 400 mm and 3200 mm, respectively. Lateral load reversals consisted of one cycle at each of the drift ratios of 0.125% and 0.25%, and two cycles at drift ratios from 0.5% with increment interval of 0.5% to 5.5%. Here, the drift ratio δ was defined as the loading displacement D divided by the specimen shear span L, i.e., $\delta = D/L \times 100\%$. In addition, the constant axial load was imposed by a hydraulic jack system during testing. Note that the external axial load simulates the permanent load of the bridge superstructure and the self-weight of the column, thus referred to as the gravity load N_G in this study.

Also shown in Fig. 1 (a) was a photograph of the column segment. Ten corrugated steel ducts with inner diameters of 60 mm were embedded in the segment for passage of longitudinal steel rebars. These corrugated ducts would be grouted by cementitious grout, of which the 3-day compressive strength was 45.5 MPa. In addition, there was a smooth duct with a diameter of 100 mm at the center of the segment. This duct was used to house the un-bonded post-tensioned tendons which consisted of six ϕ15.2 mm seven-wire strands. Therefore, by deducting the area of the central duct, the gross cross-sectional area A_g of the PSBC specimen was calculated as 0.23 m^2. As indicated in Fig. 1(b), the column segment was confined by ϕ10 mm steel overlapping hoops with a spacing of 100 mm. Furthermore, fourteen ϕ10 mm steel positioning bars were embedded in the segment to position the hoops and reduce the long-term deformation due to creep and shrinkage.

Table 1 lists the design parameters of the three specimens. The first specimen, HS0N1, was designed as a conventional NSR-PSBC which only incorporated normal-strength steel reinforcement. As shown in Fig. 1(b) and Table 1, HS0N1 was longitudinally reinforced with six ϕ16 mm and four ϕ25 mm normal-strength rebars. Accordingly, the high-strength steel reinforcement ratio ρ_H and the normal-strength steel reinforcement ratio ρ_N were 0% and 1.37%, respectively. Here, A_g was used to compute the ρ_H and ρ_N. The second specimen HS1N1 and the third specimen HS1N2 were designed as HR-PSBCs. As illustrated in Fig. 1(b), these two specimens had the same longitudinal reinforcement, i.e., six ϕ16 mm normal-strength rebars and four ϕ25 mm high-strength rebars. Table 1 shows that the ρ_H and ρ_N of the two specimens and were 0.85% and 0.52%, respectively. Therefore, the total reinforcement ratio $\rho_H + \rho_N$ for either HS1N1 or HS1N2 was 1.37%, which was the same as that of the first specimen. Furthermore, the total reinforcement ratio $\rho_s = 1.37\%$ satisfied the requirement of the AASHTO LRFD Bridge Design code, i.e., $1\% \leqslant \rho_s \leqslant 4\%$ [25].

Besides the longitudinal reinforcement, the second design parameter of the specimens was the gravity load imposed by the vertical hydraulic jack. As summarized in Table 1, the gravity loads N_G for HS0N1 and HS1N1 were $0.1f'_cA_g$ (i.e. the axial compression ratios were 0.1), typical for a high-way bridge column; while N_G for HS1N2 was $0.2f'_cA_g$ (i.e. the axial compression ratio was 0.2), typical for a railway bridge column. Here, $f'_c = 31.1$MPa was the 28-day compressive strength of the concrete. In addition, the pre-stressing forces N_P for all the specimens were $0.1f'_cA_g$. The N_P was selected such that the $N_G + N_P$ for a certain specimen would not exceed $0.3f'_cA_g$ to avoid severe P-Delta effects [22].