Engineering Structures 166 (2018) 441–453

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic performance of precast concrete bridge columns with quasi-static cyclic shear test for high seismic zones

Tiantian Li[b], Hongya Qu[b], Zhiqiang Wang[a,*], Hongyi Wei[a], Shichi Jiang[a]

[a] Department of Bridge Engineering, Tongji University, Shanghai, China
[b] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, MO, USA

ARTICLE INFO

Keywords:
Bridge column
Segmental construction
Prestressing steel
Seismic performance
Finite element method
Shear strength

ABSTRACT

In this study, six 1/3-scale short bridge column specimens are investigated for shear strength under the same quasi-static cyclic loading protocol. The specimens consist of one cast-in-place (CIP) reference column and five precast columns, and the precast columns are designed with different connection approaches. The test includes the comparison between the specimens with or without shear keys, bonded or unbonded prestressing tendons, and column or footing embedment. Test results show that the shear strengths of precast columns using only mild reinforcement are emulative of the CIP column. Shear keys employed in the connection do not retain significant improvement in terms of hysteretic behavior, while specimens with prestressing tendons possess higher shear strength but lower ductility. The unbonded prestressing tendon provides unique self-centering capability with good energy dissipation. Finite element models of the columns were created with ANSYS by considering the bond-slip effect between reinforcement and concrete, contact behavior of connection surface, and material nonlinearity, depending on different structural details. The models can effectively simulate damage development under monotonic loading, and the load-displacement curves are in good agreement with the backbone curves of the test results.

1. Introduction

In recent years, precast concrete (PC) segmental construction of bridge columns becomes popular in congested urban and environmentally sensitive areas due to its minimum traffic disruption, high construction quality, low work zone safety risk and limited environmental impact. However, its widespread use in seismic regions is hindered, because knowledge of its shear strength and availability of appropriate design guidelines under earthquakes is lacking.

Shear strength of conventional cast-in-place (CIP) bridge columns has been extensively studied [1–6]. Results of these studies indicate that shear strength of CIP bridge columns depends on the column aspect ratio (shear span-to-depth ratio), the axial load level, the amount of longitudinal and transverse reinforcement and the flexural displacement ductility factor. Based on these observations, different shear-strength equations have been developed, such as Priestley model [5], in which shear strength of a bridge column includes three independent components: a concrete component related to displacement ductility, an axial load component related to the column aspect ratio, and a truss component related to ratio of transverse reinforcement. Shear design is an important part of capacity design under earthquakes. Systematical shear design of CIP bridge columns, as well as shear-strength equations, is provided by different bridge seismic design specifications, such as AASHTO, Caltrans, EC 8-part2 [7] and New Zealand Code [8].

Despite the extensive studies and the sound specifications about shear strength of CIP bridge columns in seismic regions, the research on PC bridge columns is meager. In addition, due to the presence of connecting joints between segments, the influence of interface friction, shear keys, dry or epoxied joint and the amount of longitudinal reinforcement crossing through the joints should be considered regarding the shear behavior of the entire PC bridge column and shear mechanism of segmental joints. Therefore, differences of shear behaviors between PC and CIP bridge columns are expected to exist, and thus it is imperative to explore shear behavior of PC bridge columns for its wide application in seismic regions.

Shear strength of single-keyed joints between PC bridge deck segments is studied [9]. A group of five full-scale male-female single-keyed specimens is match cast and tested. It is observed that, for all specimens, the single key is sheared off and the male and female parts are separated from the concrete near the joint instead of the joint interface. The epoxied joint interface of the specimen enables the cross-section to reach its monolithic shear strength. A series of full-scale joints between

* Corresponding author at: Department of Bridge Engineering, Tongji University, 1239 Siping Rd., Shanghai 200092, China.
E-mail address: wangzhiq@tongji.edu.cn (Z. Wang).

https://doi.org/10.1016/j.engstruct.2018.03.086
Received 20 November 2017; Received in revised form 26 March 2018; Accepted 28 March 2018

PC girder segments are tested under different confining stress levels to investigate their shear behavior, including flat and keyed, dry and epoxied, and single-keyed and multiple-keyed joints [10]. It is concluded that shear capacity of joints is enhanced with the increased confining stress. Epoxied joints have consistently higher shear strength than dry joints, but they are more susceptible to brittle failure. The normalized average shear capacity of keys in multiple-keyed dry joints is always lower than that in single-keyed dry joints under the same stress level. However, the normalized average shear capacity of keys in multiple-keyed epoxied joints is comparable to that in single-keyed epoxied joints. This is because that the epoxy mitigates matching imperfections between the male and female parts of the multiple-keyed specimens, resulting in the increase of the joint strength and stiffness and the uniform distribution of shear load among the keys. The difference of shear behavior between dry and epoxied joints is also studied [11]. The test results show that dry joints fail at a lower ultimate load than epoxied joints, but they possess a higher ductility. Moreover, the adhesive strength of epoxy is nearly equal to, if not greater than, the concrete shear strength.

Besides the previous single joint specimens, PC segmental bridge superstructures are also tested to explore shear behavior of joints. A full-scale destructive test of a PC segmental box girder deck with dry joints and external tendons is conducted [12]. The test results show that structures with dry joints and external tendons possess substantial ductility in deflection and joint opening, which will give sufficient advanced warning before failure. Large-scale experimental investigations of prestressed PC segmental bridge superstructures are conducted to study the seismic performance of joints [13,14]. Cracking of the concrete cover adjacent to the joint is observed, rather than opening of the epoxied joint interface. The joints are able to tolerate significant repeated openings and closures under cyclic loading without failure, and the PC segmental superstructure can undergo significant seismic displacements without failure. Similar observations can be found in [15], in which nine specimens of PC segmental beams with external tendons are tested. It is concluded that the failure of dry joints occurs right at the joint interface, while that of epoxied joint is developed in the concrete adjacent to the joint interface.

Nonlinear finite element (FE) analyses are also conducted to facilitate the research. CIP bridge columns are simulated using a continuum plasticity-based isotropic damage model, which is used to represent inelastic behavior of the concrete [16,17]. The unbonded post-tensioned tendons are modeled as truss elements. The top node is coupled to the loading beam, and the bottom node is restrained to represent the anchorage in the foundation [18,19]. Flat joints between PC post-tensioned segments are analyzed [20]. A joint model, including coulomb failure criterion and shear stress model, is developed to predict the inelastic behavior of segmental joints. Single-keyed and multiple-keyed epoxied joints are simulated numerically to study their shear behavior [21]. A linear elastic material model is used to model the epoxy, since the tensile and shear strength of the epoxy are much higher than those of the concrete. A FE analysis is reported on the fracture behavior of keyed dry joints under shear, including one to seven keys [22]. A hard contact model is used to model the contact in the surface normal direction, which is able to separate and to come in contact again. However, this model neglected the penetration of one surface into the other one and the transfer of tensile stress across the joint interface. The coulomb friction model with a friction coefficient of 0.72 is used to consider the tangential behavior between concrete surfaces.

Based on the literature review, the studies of shear strength are extensive and comprehensive regarding traditional CIP structures. In terms of PC bridges, the majority focused only on superstructures or single joints, and few tests have been performed to investigate the integrated design of the entire bridge column structure. Solely studying the joint design cannot fully understand its behavior when applied to the bridge columns, and therefore it is necessary to perform a shear study targeting real-world application to both investigate and verify the joint designs. Moreover, such systematic comparison among five connection approaches has never been performed to the best of the authors' knowledge. In this study, six 1/3-scale bridge columns including one CIP reference and five PC approaches are tested under quasi-static cyclic shear loading. The columns are designed based on actual applications in Highway S6 of Shanghai, China. The five PC specimens are connected by grouted splice sleeve couplers (GSSCs), unbonded post-tensioned tendons (UPTs) or bonded post-tensioned tendons (BPTs). Grout-filled or epoxied joints, with or without shear keys, and different locations of joints are investigated regarding shear mechanism of joints and shear performance of the entire PC bridge column. Solid FE models are also created, calibrated and verified by experimental results to further understand the structural behavior.

2. Quasi-static testing

2.1. Specimen details

The design of specimens is based on the urban viaduct in practical applications of Shanghai, China. This study belongs to a series of studies for investigation and verification purposes [23,24]. All the specimens are in 1/3-scale for consistency, considering the experimental feasibility and limitation [25,26]. The detailed similitudes of each parameter are given in Table 1.

The actual compressive strength of the concrete for each specimen is obtained based on the coupon tests of three 150 mm × 150 mm × 150 mm concrete cubes prior to each column test. The tested compressive strengths of concrete for specimens #1-#6 are 52.4 MPa, 50.6 MPa, 48.6 MPa, 54.2 MPa, 53.8 MPa, and 51.7 MPa, respectively. The average tested compressive strength of concrete for all specimens is 52 MPa. There are two types of mild reinforcement, and they are hot-rolled plain bar with nominal yield strength of 235 MPa (HPB235) and hot-rolled ribbed bar with nominal yield strength of 400 MPa (HRB400). Nominal elastic moduli of HPB235 and HRB400 are 210 GPa and 200 GPa, respectively. Tension tests of three coupons from each type of steel are performed. The average measured yield stresses of HPB235 and HRB400 are 245 MPa and 421 MPa, and the average measured ultimate stresses are 399 MPa and 610 MPa. The average measured elastic moduli of HPB235 and HRB400 are 215 GPa and 203 GPa. Strain values of HPB235 and HRB400 at initial strain hardening are 0.00273 and 0.00355, and strain values at ultimate stress are 0.012 and 0.017. High-strength grout is used for the connections, which has an average compressive strength of 104 MPa based on three tested cubes for each specimen that has GSSCs. The high-strength and low-relaxation 15.2 mm-diameter (D15.2) seven-wire strands are used for the UPT and BPT, and the nominal tensile ultimate strength is 1860 MPa.

The design details of all specimens are shown in Fig. 1, including reinforcement arrangement connection placement, and tendon deployment. Specimen #1 is the CIP column that serves as the reference for comparison purpose. Specimens #2 and #3 represent two typical design approaches, which are the column-to-footing and column-to-column connections with GSSCs. The construction process is completed through reinforcement binding, connection positioning and grouting. Moreover, compared to the column-to-footing connection (specimen #2), the column-to-column connection (specimen #3) is considered to be more susceptible to local buckling and fracture of the reinforcement, as well as relative displacement between the segments. To increase the shear capacity of the connections, two strategies are introduced to

Table 1
Design similitudes of the specimens.

C_l	C_x	C_E	C_σ	C_ε	C_p	C_M	C_q	C_K
1/3	1/3	1	1	1	1/9	1/27	1/3	1/3

Note: subscript l is length, x is displacement, E is elastic modulus, σ is stress, ε is strain, p is force, M is moment, q is distributed load, and K is stiffness.