Engineering Structures 99 (2015) 413–422

Contents lists available at ScienceDirect

Engineering Structures

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

UHPC-filled duct connections for accelerated bridge construction of RC columns in high seismic zones

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ARTICLE INFO

Article history:
Received 9 December 2014
Revised 30 March 2015
Accepted 11 May 2015
Available online 27 May 2015

Keywords:
ABC
RC bridge column
UHPC
Duct
Seismic performance
Cyclic test
Analysis
New bond–slip method

ABSTRACT

Substantial attention is being paid to accelerated bridge construction (ABC) in the United States because ABC offers many advantages such as shorter onsite construction time, lower traffic impact, and higher quality structural members. Prefabricated bridge elements and systems are one of the most important ABC components. However, scarcity of seismic performance data for prefabricated element connections has limited the application of ABC in high seismic zones. In this paper, seismic performance of a new column-to-footing connection was experimentally investigated by cyclic testing of a half-scale precast reinforced concrete bridge column connected to the footing incorporating an ultra-high performance concrete (UHPC) filled duct connection. The seismic performance of the test model was comprehensively compared with a reference cast-in-place model. Furthermore, connection performance of another half-scale precast bridge column utilizing this type of connection was presented. The former model was design and tested to specifically evaluate the seismic performance of the column utilizing new column-to-footing connection and the latter column was built with eight different materials to investigate the seismic performance of a low-damage precast column detailing for high seismic regions. Nevertheless, UHPC-filled duct connections were incorporated in the column-to-footing connections of the both test models. The test results showed that the UHPC-filled duct connections were emulative of the conventional connection. An analytical model was developed using a finite element computer program to simulate cyclic response of the column. The model incorporated a new analytical technique to include the effect of bond–slip through a modified stress–strain relationship for reinforcing steel. The calculated and measured force–displacement relationships of the column showed good correlation.

1. Introduction

Traffic impact and onsite construction time can be substantially reduced using accelerated bridge construction (ABC) techniques. Reduction of total project delivery time and improvement of material quality are other benefits of ABC [1]. Because of these and other advantages, ABC has been gaining substantial momentum in the United States. ABC relies heavily on offsite prefabricating of components, shipping to the site, and onsite installation.

Implementation of ABC for bridge columns in the moderate and high seismic regions has been limited due to a lack of performance data pertaining to column ends connections, which must be able to transfer seismic forces while allowing the column to have large inelastic deformations. Marsh et al. [2] evaluated suitability of seven ABC column connection types to be incorporated in moderate and high seismic zones: bar couplers, grouted ducts, pocket connections, member socket connections, hybrid connections, integral connections, and emerging technologies. These methods have been mainly used in column to cap beam or column segment connections, and barely utilized in column-to-footing connections.

Haber et al. [3] incorporated two types of mechanical reinforcing bar splices, grouted couplers and headed reinforcement couplers, in plastic hinge of four half-scale circular reinforced concrete (RC) bridge columns that were tested to failure under cyclic loading. The test results showed that seismic behavior of the precast columns was the same as a cast-in-place (CIP) model behavior, but the grouted coupler models exhibited lower displacement capacity compared to the conventional model. The Edison Bridge was constructed in Florida using a grouted coupler system connecting columns to pier caps [4]. Grout-filled duct connections were incorporated in a few bridges in Texas [5] and Washington [6]. Experimental results have shown that the grout-filled duct connection and the pocket connection are

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http://dx.doi.org/10.1016/j.engstruct.2015.05.018

emulative of cast-in-place construction [7]. Socket connections were used in an actual bridge in the State of Washington to connect precast columns to footings [6]. Seismic performance of a column-to-footing connection with elastomeric rubber plastic hinge was investigated by Motaref et al. [8]. This connection is categorized as an emerging technology-type connection.

Grout-filled duct connections were the focus of this paper. In this type of connection, column straight longitudinal bars are anchored in the grouted corrugated ducts installed in the connecting members. Bond behavior and performance of the grout-filled duct column-to-cap beam connection were investigated in several studies confirming that the connection is a suitable substructure ABC connection in seismic regions [5,7,9–11].

Cap beams are usually sufficiently deep to accommodate long ducts to fully anchor the column longitudinal bars. However, an alternative moment-resisting connection is necessary to connect precast columns to either shallow cap beams or footings. Tazarv and Saiidi [12] investigated the bond behavior of ultra-high performance concrete (UHPC) filled duct connections by testing 14 pullout specimens. UHPC is a class of fiber reinforced concrete with a minimum 150-MPa (22,000-psi) specified compressive strength with improved durability, toughness, and corrosion resistance over conventional concrete [13]. UHPC is a mix of Portland cement, sand, silica fume, quartz, water, superplasticizer, and usually 2% volumetric high-strength steel fibers but the size of aggregates is in the scale of micron. The length of fibers is usually 12 mm (0.5 in.). Furthermore, UHPC exhibits significantly higher compressive strain capacity compared to conventional concrete. The tensile strength of UHPC is approximately two times higher than the conventional concrete tensile strength with 0.8% tensile strain capacity [14,15]. The pullout tests in [12] showed that the bar embedment length can be reduced by at least 50% compared to either conventional or the normal-grout-filled duct connections. Furthermore, it was found that the bond strength of a bar embedded in UHPC is eight times stronger than that of conventional concrete. Design embedment length for deformed bars in UHPC-filled duct connections was also proposed in that study [12].

In this paper, the seismic performance of a half-scale precast RC bridge column connected to a footing using a UHPC-filled corrugated duct connection was first experimentally investigated and the cyclic response of the column was comprehensively compared with that of a reference cast-in-place column. Furthermore, connection performance of another half-scale precast column in which a UHPC-filled duct column-to-footing connection was used is presented. Next, an analytical model was developed to evaluate modeling methods that would best reproduce the measured response. A new simple technique was developed and incorporated in the analytical model accounting for bond–slip deformations in RC members.

2. Experimental program

2.1. Description of column model

A half-scale precast RC bridge column referred to as "PNC", an acronym for Precast column with No Coupler, incorporating a UHPC-filled duct connection was constructed and tested at the University of Nevada, Reno (UNR) under reversed cyclic loading to failure. The column was designed similarly to a conventional cast-in-place column based on the Caltrans Seismic Design Criteria [16] for a design displacement ductility of seven. Fig. 1 shows the PNC column base connection in detail. The column height from the footing surface to the center of the loading head was 9 ft (2.74 m). The diameter of the column was 24 in. (610 mm), which leads to an aspect ratio of 4.5. The column was reinforced longitudinally with 11-No. 8 (11-Ø25 mm) bars and

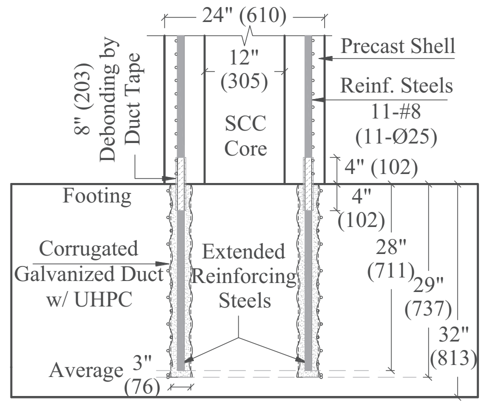

Fig. 1. PNC column base connection, unit: in. (mm).

transversely with No. 3 (Ø10 mm) spiral at a 2-in. (51-mm) pitch resulting in longitudinal and transverse steel ratios of 1.92% and 1.03%, respectively. The design axial load index, which is the ratio of the axial load to the product of column cross-section area and the design compressive strength of concrete, was approximately 10%. The clear cover was 1.5 in. (38 mm) in the column.

Corrugated galvanized steel ducts with a nominal 3-in. (75-mm) diameter conforming to ASTM A653 [17] with 26-gauge (0.0179-in. or 0.45-mm) wall thickness were used in the footing and later were filled with UHPC. Transverse reinforcement, similar to the column transverse reinforcement was used around the ducts. The column longitudinal bars were extended 28 in. (711 mm) at the base to be inserted into the ducts. However, the required embedment length to fracture the anchored bar was only 19 in. (483 mm) based on the design equations presented in Tazarv and Saiidi [12] assuming: (1) the footing concrete compressive strength is 5000 psi (34.5 MPa), (2) the UHPC compressive strength is 20,000 psi (137.9 MPa), and (3) No. 8 (Ø25 mm) bars have an ultimate strength of 110 ksi (758.4 MPa). Note that these values were utilized for design of the UHPC-filled duct connection incorporated in PNC and the measured strength of these materials are presented in the following section. It was mentioned that bond strength of UHPC is eight times higher than conventional concrete bond strength. Therefore, in order to limit potential localized failure and spread yielding, 4 in. (102 mm or $4d_b$ in which d_b is the column longitudinal bar diameter) of the column longitudinal bars were debonded above and below the column-footing interface using plastic tape (Fig. 1). Therefore, the effective bar embedment length in the UHPC-filled duct connection of PNC was 24 in. (610 mm), only 5 in. (127 mm) longer than the design development length.

To minimize the precast column weight and to facilitate transportation, a hollow core circular section with a 6-in. (152-mm) wall thickness was constructed. The column core was subsequently filled with self-consolidating concrete (SCC) after installing the shell on the footing. The construction stages of the PNC model were: (1) casting the footing with duct cage installed inside the footing (Fig. 2a), (2) casting the hollow core column with extended longitudinal bars at the column base (Fig. 2b), (3) filling the ducts with UHPC using a tremie-tube method then erecting the precast column (Fig. 2c), and (4) filling the core and casting the head, both with SCC.

2.2. Test setup and loading protocol

A 220-kip (978 kN) servo-hydraulic actuator was used in a cantilever configuration test setup (Fig. 3) to apply lateral loads to the column. An axial load of 200 kips (890 kN) was applied to the