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High-strength concrete exterior beam-column joints with high-yield strength steel reinforcements

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ABSTRACT

This paper presents the experimental and analytical investigations carried out on high-strength concrete (HSC) beam-column joints with Grade 700 longitudinal rebars in beams and columns. Five full-scale exterior RC beam-column joints with various reinforcement detailing were designed according to the special seismic provisions of ACI 318-14. The variables in test specimens include the concrete compressive strength, yield strengths of reinforcement and the axial compression levels. The test specimens were subjected to constant column axial loading and quasi-static lateral load reversals. The performance of each test assembly was examined in terms of cracking patterns, lateral loading capacity, strain profiles of the reinforcements, secant stiffness, energy dissipation capacity, and the bond performance. All specimens displayed ductile failure mode and it was concluded that the use of high-strength concrete and the applied axial compression loading could improve the bond condition of the specimens. Parametric studies were performed to study the influence of various parameters on the strength, required development lengths and energy dissipation capacity of the specimens. An explanation for the observed cracking pattern and further analytical investigations using a strut-and-tie modeling was conducted.

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1. Introduction

Most studies on the behavior of reinforced concrete (RC) beam-column joints focused on the test specimens designed with normal-strength steel reinforcements with yield strength of up to 420 MPa. In recent years, the use of high-yield strength reinforcing rebars has been introduced to the construction industry sparking extensive research in this area. Utilizing high-strength steel (HSS) reinforcements proved to be effective in solving the steel congestion problem by reducing the required steel, especially in beam-column connections. In spite of the increased interest in using HSS reinforcements, the seismic provisions for special moment frames in ACI 318-14 [1] set a limit of 420 MPa for longitudinal reinforcements and allow the yield strength of confining reinforcements up to 689 MPa only. The limit is set to be 500 MPa for longitudinal reinforcing bars in other seismic design codes such as EC8 [2]. However, the use of longitudinal steel reinforcement with yield strength of greater than 500 MPa still requires further research. Ehsani et al. [3] presented the first reported study on the behavior of moment-resisting frames constructed with high-strength concrete. The effect of confining reinforcements and joint hoops in high-strength concrete members has been investigated by Li et al. [4] and Hwang et al. [5]. Some other test programs [6–8] have been reported to assess the bond condition in beam-column joints with Grade 500 longitudinal reinforcements while Hwang et al. [9] tested beam-column joints with Grade 600 beam longitudinal reinforcing rebars. Nevertheless, experimental evidence of seismic behavior of beam-column joints with HSS as longitudinal reinforcements is still inadequate. It is known that the increased bond-slip of bars, decreased hysteretic energy dissipation and lower shear strength of the joints are the key obstacles behind designing beam-column joints utilizing HSS reinforcements. However, the critical issue in using HSS longitudinal reinforcements in exterior joints is the increased required anchorage length of the beam rebars in the joint region. In the current study, a combination of HSC coupled with the use of HSS reinforcements has been introduced as a possible solution. Previous studies on seismic performance of beam-column subassemblies with high-strength steel reinforcement [9,10] were conducted with normal-strength concrete and zero column compression loading.To prevent bond failure in exterior beam-column joints, the diameter of beam longitudinal bars passing through joints, d_{bL}, is limited in EC8 [2] as follows:

$$\frac{d_{bL}}{h_c} \geqslant \frac{7.5 f_{ctm}}{\gamma_{rd} . f_y} .(1 + 0.8 . \nu_d) \tag{1}$$

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Notation

A_g	gross cross-sectional area of the RC column	h_c	depth of RC column section
DR	story drift ratio	l_{dh}	development length of longitudinal beam rebars
d_b	diameter of reinforcing bar	P	axial compression force on column
f'_c	compressive strength of concrete	ξ_{eq}	equivalent viscous damping
f_u	ultimate strength of steel reinforcement	γ	joint shear strength factor
f_y	yield strength of steel reinforcement		

where h_c is the column width, f_{ctm} is the mean value of the tensile strength of concrete, f_y is the yield strength of steel reinforcement, ν_d is the normalized design axial force in the column, and γ_{rd} is the over-strength factor taken as 1.0 or 1.2.

ACI 318-14 [1] has specified a minimum development length l_{dh} of a 90 degree hook bar as mentioned in Eq. (2a) and a compressive development length in case of reversed cyclic loading in exterior joints as mentioned in Eq. (2b).

$$l_{dh} \geqslant f_y d_b / 5.4\sqrt{f'_c}(\text{MPa}) \tag{2a}$$

$$l_{dh} \geqslant f_y d_b / 4\sqrt{f'_c}(\text{MPa}) \tag{2b}$$

An analytical approach is used to take into account the effect of column compression loading in the above equations with a novel equation being proposed. Five full-scale exterior joints reinforced with high-strength longitudinal bars with $l_{dh}/d_b = 20.2$ and 24.2 were tested. The l_{dh}/d_b values satisfied the requirements of ACI 318-14 [1] and ACI 352-02 [11]. The applicability of ACI 318-14 provisions when high-strength bars are used is to be verified. The aim of this paper is to provide experimental evidence of the behavior of full-scale exterior beam-column joints reinforced with HSS bars subjected to cyclic loading and with various design parameters. The test specimens were designed with high grades of concrete in order to investigate the beneficial effect of using HSC coupled with HSS reinforcements. The validity of ACI 318-14 design requirements for RC joints with HSS reinforcements is examined.

2. Description of test program

2.1. Specimen details

Five specimens of the same dimensions, but different reinforcement details and different strengths of the material were cast in place to present a typical exterior beam-column joint of an RC building structure. With most of the gravity load sustained by interior and exterior gravity frames, the bending moment induced by gravity load is small relative to that induced by seismic loading. As a result, the point of inflection in the beams is located very close to the beam mid-span. The specimens were labeled as EN80, EH80, EH80A, EH60 and EH60A. The letter "E" indicates the exterior type of the joints. The letter "H" stands for high-strength steel reinforcement in specimens and letter "A" indicates the presence of column axial compression loading. The grade of concrete in each specimen is shown as a number in its label. The beam span was 4.8 m and the height of the column was 3.3 m in all of the test specimens. The specimens were designed based on the strong column-weak beam requirement and detailing requirements of ACI 318-14 [1] and ACI 352-02 [11] to ensure that plastic hinges would occur in beams at the column faces. The specimens were designed in a way that the role of various design parameters including the concrete grade, yield strength of steel reinforcements, and the axial loading level could be studied.

2.2. Reinforcement details

As shown in Fig. 1, beams were reinforced using 2T16 (16-mm diameter) bars at the bottom and 4T16 at the top in Specimens EN80, EH80 and EH80A. However, in Specimens EH60 and EH60A, 2T19 bars were used as the top and bottom beam reinforcements. Beam bars were anchored within the joint region. In the column section of EN80, a combination of Grade 500 bars of diameter T20 and T16 was used as longitudinal reinforcements, while a combination of Grade 700 bars of diameter T22, and Grade 500 bars of T16 were utilized in the column design of all the other specimens. Transverse reinforcements in beams and columns were designed according to the provisions of ACI 318-14 [1] for the purpose of resisting shear, confining concrete and prevent premature longitudinal bar buckling. Transverse reinforcements in the joint region were designed according to the recommendations of ACI 352-02 [11]. 5 sets of high-strength hoops with a spacing of 65 mm were used in joint regions of EN80, EH80 and EH80A while 4 sets of the same hoops with a spacing of 85 mm were utilized in EH60 and EH60A. Table 1 summarizes the design parameters of the specimens.

2.3. Material properties

The target concrete compressive strength of the specimens was 60 and 80 MPa. Deformed steel bars of yield strength $f_y = 550$ MPa and $f_y = 700$ MPa were utilized as longitudinal reinforcement of beams and columns. The transverse reinforcement utilized in beams and columns included R6 and R10 mild steel bars with $f_y = 550$ MPa and $f_y = 700$ MPa. The percentage of carbon is 0.24% and 0.32% in Grade 500 and 700 MPa steel, respectively. The percentage of phosphorus, sulfur, nitrogen, and copper is 0.055, 0.055, 0.014, and 0.85 in steel reinforcement with both grades. The reinforcing bars were tested under uniaxial tension and the measured parameters of the steel bars are mentioned in Table 2. The behavior of test specimens, especially in terms of the bond performance, is quite sensitive to the surface properties of reinforcing bars. These parameters include the type of deformation, depth of rib, and spacing of the rib. Surface properties of the reinforcing bars are summarized in Table 3.

2.4. Test setup and loading procedure

The test setup is shown in Fig. 2. The bottom of the column is pinned to the strong floor and the beam end is connected to the strong floor using a vertical steel link which only restrains the beam vertical movements and permits the rotation and free horizontal translation of the beam. Each test specimen was subjected to quasi-static reversed cyclic simulated earthquake loading as shown in Fig. 2. The loading sequence adopted in this testing program follows the typical quasi-static test sequence used in previous research for many years. In the current study, the specimens are subjected to predetermined numbers of displacement controlled quasi-static loading cycles to predetermined displacement

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