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Experimental study of cyclic behavior of high-strength reinforced concrete columns with different transverse reinforcement detailing configurations

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ABSTRACT

Detailing of transverse reinforcement is essential to ensure ductile behavior of reinforced concrete (RC) members, particularly for columns with large displacement demanding under high axial loading level. Requirements of reinforcing details are even important for high strength concrete due to its brittleness nature. This paper presents experimental study regarding cyclic behavior of high strength RC columns with different transverse reinforcement detailing layouts. The three high strength RC columns consisted of different transverse reinforcement detailing configurations, which were conventional closed-hoops, butt-welded hoops and single closed-hoop with cross-ties, respectively. The columns were made of high-strength concrete with compressive strength of 70 MPa and high-strength steel with yield stresses of 685 MPa and 785 MPa for longitudinal and transverse reinforcement, respectively. Cyclic displacement static tests subjected to high axial compression loading of $0.3A_gf'_c$ were conducted to verify the adequacy of transverse detailing. The performance of the column with conventional closed-hoops and that of the column with butt-welded hoops, which were compliant of ACI 318-14, were almost identical and met the performance criteria required by ACI 374. In contrast, the column with a single closed-hoop and cross-tie that was designed based on ACI 318-11 did not perform well as a ductile RC column. These results prove that the ACI 318-14 minimum requirements for confinement should be followed. In addition, butt-welded hoops are acceptable as a form of transverse reinforcement of a column, since no fracture was observed at the welded location. The current flexural and shear design equations for the RC columns are discussed and compared with the test results.

1. Introduction

The Taiwan New Reinforced Concrete (New RC) research project was launched in 2008. One of the main objectives of the New RC research project is to apply high-strength steel and concrete to RC columns in high-rise buildings [1]. The use of high-strength concrete and steel has gained attention recently due to the requirement for more available floor area, which can be achieved by limiting the size of lower-story columns in high-rise buildings [2,3]. By using high-strength concrete and steel, the column section size and reinforcement congestion can be reduced. In Taiwan, advanced technology has led to the development of high-strength concrete with a compressive stress of 70 MPa or greater. Meanwhile, deformed steel bars SD685 and SD785 with specified yield stresses of 685 MPa and 785 MPa for longitudinal and transverse reinforcement, respectively, are commercially available [2,3]. Increasing the compressive strength, however, renders the concrete more brittle, and thus greater transverse reinforcement ratio, particularly for confinement in a high-strength concrete column is necessary [4,5]. Detailing of transverse reinforcement is essential to ensure ductile behavior of RC members, particularly for columns with large displacement demanding under high axial loading level. Requirements of reinforcing details are even important for high strength concrete due to its brittleness nature.

The ACI 318-11 requirements for confinement reinforcement, however, do not specify the limit of concrete strength and axial load [6]. The results of a review of column test data conducted by Elwood et al. confirmed that the previous confinement provisions (ACI 318-11) should be changed to include axial load for designing confinement reinforcement [7]. ACI 318-14 then

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Notations

A_g	area of the column section
A_s	total area of longitudinal reinforcement
A_{sh}	total area of transverse reinforcement parallel to lateral loading direction
b_c, b_w	side dimension of the column core section and side dimension of the column section, respectively, perpendicular to lateral loading direction
C_c, C''_s	compressive force in concrete and compressive force in longitudinal steel reinforcement, respectively, in cross section of the column
d	effective depth of the column section (measured from extreme-compression fiber to centroid of extreme-layer of tensile steel reinforcement)
d′	distance from extreme-compression fiber to centroid of steel reinforcement in cross section of the column
d″	distance from extreme-compression fiber to centroid of steel reinforcement closest to extreme-compression fiber
f'_c	specified compressive strength of the concrete material
F_s	tension force in the extreme-layer of tensile longitudinal steel reinforcement in cross section of the column
F'_s	compressive or tension force in the longitudinal steel reinforcement in cross section of the column
f_y	yield stress of longitudinal reinforcement
f_{sh}	stress of transverse reinforcement used to design shear strength (limited to not exceed 600 MPa)
f_{yt}	stress of transverse reinforcement used to design confinement (limited to not exceed 700 MPa)
h	height of the column section
k	factor relating the concrete or transverse reinforcement capacity to the displacement ductility [Eqs. 12 and 12(a)]
L_c	clear height of column specimen
k_f	concrete strength factor for designing confinement reinforcement [Eqs. 8 and 8(a)]
k_n	confinement effectiveness factor for designing confinement reinforcement [Eqs. 8 and 8(b)]
M_m	factored moment modified to account for effect of axial compression load [Eqs. 10 and 10(a)]
M_n	nominal moment about an axis perpendicular to lateral loading direction (computed about the centroid of rectangular section) [Eq. 4]
M_{pr}	maximum moment probable about an axis perpendicular to lateral loading direction
M_u	moment corresponding to applied axial compression load
n_l	number of longitudinal bars around the perimeter of the column core that are laterally supported by the corner of closed-hoops or conventional cross-ties with a 135-degree hook
P_n	nominal axial compression force in column section at given eccentricity [Eq. 3]
P_o	nominal strength of reinforced concrete column at zero eccentricity [Eq. 5]
P_u	applied axial load
V_c	shear strength provided by concrete [Eqs. 9,10,11,12, and 13]
V_n	nominal shear strength [Eqs. 9,10,11,12, and 13]
V_s	shear strength provided by transverse reinforcement [Eqs. 9,10,11,12, and 13]
$V_{n,f}$, V_{pr}	shear force corresponding to the flexural strength of the column section and shear force corresponding to the maximum moment probable, respectively
α	reduction factor [Eqs. 13 and 13(a)]
α_1	factor relating the magnitude of uniform stress in an equivalent rectangular compressive stress block to the specified compressive strength of the concrete [Eq. 1]
β_1	ratio of the depth of the equivalent rectangular compressive stress block to the neutral axis [Eq. 2]
λ	factor reflecting the reduced mechanical properties of lightweight concrete (1 for normal concrete)
ρ_w	ratio of total area of tension steel reinforcement to b_w.d
X_1	ratio of the mean concrete compressive stress corresponding to the maximum axial load resisted by a concentrically loaded column to the specified compressive strength of concrete

adopted the results of the study conducted by Elwood et al. to develop the new confinement provision, in which the axial load and high-strength concrete factors are directly accounted for [8]. The new confinement provision also considers the number of longitudinal bars around the perimeter of the column core that are laterally supported by the corner of closed-hoops or cross-ties with a 135-degree hook [9]. A cross-tie is a transverse reinforcement bar with a 135-degree hook at one of its edges and a 90-degree hook at another edge. As is commonly known, the transverse reinforcement detailing may be a conventional closed-hoops model with a seismic hook at one corner or a single closed-hoop model with cross-ties [6]. Both ACI 318-11 and ACI 318-14 limit the yield stress of transverse reinforcement as 420 MPa for designing shear strength, while the use of yield stress of 700 MPa is permitted for designing confinement reinforcement. Those codes also specify not to use butt-welded hoops for ductile RC columns, since it can lead to local embrittlement of steel [6,8,10]. However, there are several advantages of using butt-welded hoops, such as the elimination of the possibility of anchor pull-out failure, and the reduction of reinforcement congestion [11].

It is worth mentioning that the amount and detailing of transverse reinforcement is critical to assure ductile behavior of RC columns under cyclic and high axial compression loading. Therefore, the cyclic behavior of high-strength RC columns using different transverse reinforcement detailing models is investigated in this study. The high-strength RC columns with high-strength steel were prepared and tested. All specimens had the same longitudinal bar configuration, while the transverse reinforcement spacing of all columns satisfied the minimum requirements of ACI 318-14 for transverse reinforcement spacing.

2. Research significance

This study investigates the lateral strength and behavior of New RC columns that use different transverse reinforcement detailing configurations under double-curvature cyclic and high axial compression loading. The three high strength RC column specimens consisted of different transverse reinforcement detailing configurations, which were conventional closed-hoops, butt-welded hoops and single closed-hoop with cross-ties, respectively. The applied axial compression ratio was 0.3. The specified concrete compressive strength, yield stress of the longitudinal reinforcing bar, and yield stress of the transverse reinforcing bar were 70 MPa, 685 MPa, and 785 MPa, respectively. This study is significant because the tests also simulated the behavior of columns in the lower stories of high-rise buildings, in which a column is subjected to high axial compression loading. In addition, research on high-strength RC columns using different transverse