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Role of concrete confinement of wide-flange structural steel shape in steel reinforced concrete columns under cyclic loading

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ABSTRACT

In this study, effects of wide-flange structural steel shapes on concrete confinement of steel reinforced concrete (SRC) columns were examined by conducting structural testing on six large-scale SRC columns under cyclic loading. Specifically, effects of the major- and minor-axis bending relative to the steel shape on the ductility and confinement effectiveness of SRC columns were investigated. Experimental results showed that concrete confinement of SRC columns were highly influenced by the bending direction. Details of the underlying confining mechanisms of SRC columns were uncovered. Findings from this study indicated that the required confinement reinforcement for the SRC columns subjected to major-axis bending could be significantly reduced, compared to that of the SRC columns subjected to minor-axis bending.

1. Introduction

Steel reinforced concrete (SRC) members, also known as concrete encased composite members, combining reinforced concrete (RC) and structural steel sections provide several advantages over traditional reinforced concrete and steel members. The concrete provides fire resistance to the steel section and restrains the steel member from buckling. On the other hand, the steel section confines the concrete core, so the confined concrete core can sustain greater compressive force and deformation. A well-confined concrete core is vital for a column to develop a satisfactory plastic hinge rotation capacity, which is one of the critical factors regarding the seismic performance of columns.

For a RC structure, the plastic hinge rotation capacity of a column could be influenced by the amount of transverse reinforcement. As the transverse reinforcement contributes shear strength of RC columns, it restrains buckling of longitudinal reinforcing bars and provides confinement to the concrete core – both are essential to the plastic hinge rotation capacity of RC columns. For a RC column in a special moment frame, ACI 318-11[1] Section 21.6.4.3 imposes spacing limits on transverse reinforcement to restrain longitudinal reinforcing bars from buckling after concrete spalling and to provide adequate concrete confinement. In addition to the spacing limits, ACI 318-11[1] Section 21.6.4.4 prescribes minimum amount of transverse reinforcement to be used in potential plastic hinge regions.

The determination of the amount of transverse reinforcement of SRC columns in order to provide a satisfactory ductility under seismic events has been a challenge over the years. The ACI and AISC specifications [1,2] provide design equations for determining the amount of transverse reinforcement required for columns in order to warrant a satisfactory ductility. However, these requirements were either developed for RC columns, such as ACI 318-11[1] requirements, or were evolved from the ACI equations, such as AISC 341-05[2] requirements. As a result of that, these requirements may not be entirely suitable to SRC columns. An essential source contributing to this ineptness comes from the negligence of steel shape effects on concrete core confinement and flexural curvature ductility. Hence, confinement requirements for SRC columns should differ from those for RC columns. When designing SRC columns subjected to seismic loading, engineers may choose to use a RC building code, such as ACI 318-11[1], or a structural steel design code, such as AISC 341-05[2]. For rectangular RC members, in the regions where plastic hinges may be developed, the ACI design code[1] requires a minimum total cross-sectional area of transverse reinforcement, which shall not be less than the values obtained by the following equations:

$$A_{sh} = 0.3sb_c(f'_c/f_{yt})(A_g/A_{ch} - 1) \quad (1)$$

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Nomenclature

A_b	cross-sectional area of steel bars
A_{ch}	cross-sectional area measured to the outside edges of transverse reinforcement
A_g	gross area of the cross section
A_s	cross-sectional area of structural steel core
A_{sh}	total cross-sectional area of transverse steel bars
b_c	cross-sectional dimension of member core measured to the outside edges of the transverse reinforcement
b_f	width of the flange of steel shape
d	depth of the steel shape
F_y	specified minimum yield stress of the structure steel core
F_{ysr}	specified minimum yield stress of the ties
f'_c	specified compressive strength of concrete
f_{yh}	yield strength of transverse steel bars
H_{max}	maximum lateral load
H_n	lateral load obtained by M_n/L
h_{cc}	cross-sectional dimension of the confined core measured center-to-center of the tie reinforcement
L	length of the column specimen measured from the lateral loading point to the face of the footing
M_{exp}	flexural capacity of a SRC column obtained from the experiment
M_{na}	nominal flexural capacity of a SRC column obtained from the P-M diagram using the actual material properties
P_n	nominal compressive strength of the composite column calculated in accordance with AISC360-10
s	center-to-center spacing between transverse reinforcement
t_f	thickness of the flange of steel shape
t_w	thickness of the web of steel shape
α	drift ratio – ratio of the lateral displacement, Δ, and vertical height of the horizontal actuator, L
Δ	lateral displacement at the level of the horizontal actuator
Δ_u	ultimate lateral displacement
Δ_y	yield lateral displacement
θ_p	plastic hinge rotation

$$A_{sh} = 0.09 s b_c (f'_c/f_{yt}) \tag{2}$$

The above ACI 318-11[1] equations are intended to provide sufficient confinement in order to maintain a certain level of axial load bearing capacity after spalling of the concrete cover. Ricles and Paboojian [3] experimentally studied seismic performance of SRC columns. Although some SRC columns in their study possessed transverse reinforcement less than the ACI requirements, the columns exhibited high ductility, suggesting that required transverse reinforcement for SRC columns can potentially be reduced.

Similarly, AISC 341-05[2] requires a minimum area of transverse reinforcement for SRC columns used as highly ductile members. The expression of the AISC equation is as follows:

$$A_{sh} = 0.09 s h_{cc} (f'_c/F_{yh})(1 - A_s F_y/P_n) \tag{3}$$

The equation was developed based on one of the ACI equations with a reduction factor considering the yield strength of the structural steel core. Nevertheless, this minimum transverse reinforcement requirement can be waived if the structural steel core of the composite member can alone resist the expected gravity load. In addition, Eq. (3) indicated that the required minimum reinforcement area, A_{sh}, is a function of the nominal compressive strength of the composite column, which requires the determination of the effective length factor. However, the method used for determining the effective length factor for SRC columns requires tedious calculations, yet it is not rigorously accurate for evaluating actual column buckling strength owing to the presumed simplified buckling conditions used in the development of the effective length factor. While the AISC equation offers an alternative to determining the required amount of transverse reinforcement for SRC columns, AISC 341-05[2] indicates that the AISC transverse reinforcement provisions are considered to be conservative and recommends that further research is required to determine to what degree the transverse reinforcement can be reduced. It should be noted that the AISC equation was developed based on Eq. (2), which typically controls the required transverse reinforcement when the column size is larger than 800 mm × 800 mm. As Eq. (3) is simply a reduction of Eq. (2), the transverse reinforcement requirement for SRC columns based on the AISC equation is ideally for large columns.

Plastic hinges can be formed at columns, especially at the bottom of columns in the first story, which is crucial to provide ductility to structures under severe seismic events. Although future research on transverse reinforcement requirements of SRC columns was recommended by AISC[2], past research in this area has been limited. The current study was intended to fill this research gap. As part of this study, an experimental program was carried out to investigate relationships between SRC column ductility and transverse reinforcement amount. More specifically, this study examined effects of the bending direction relative to the structural steel shape on transverse reinforcement requirements for SRC columns.

2. Experimental program

2.1. Specimen design

Six large-scale SRC column-footing assemblages were fabricated and tested under cyclic loading. Fig. 1 shows the configuration of the column-footing assemblage. Dimensions of the column were 450 mm × 450 mm × 2270 mm, and dimensions of the footing were 630 mm × 800 mm × 2200 mm. As shown in Fig. 2, a structural steel wide-flange section H260 × 200 × 9 × 14 ($d \times b_f \times t_w \times t_f$ in mm) and eight #6 (D19) rebars were used in the column. Materials used for the steel shapes and steel bars were A572 Grade 50 and A615 Grade 60, respectively. The specified compressive strength of concrete was 34 MPa. The width-to-thickness ratios of the flange and web of the used H260 × 200 × 9 × 14 were 7.1 and 22.9, respectively, satisfying the requirements for highly ductile members prescribed by AISC 341-05[2], which limits the width-to-thickness ratios of the flange (b/t) and web (h/t_w) of wide-flange sections for highly ductile members to $0.3\sqrt{(E/F_y)}$ ($b/t \leqslant 7.2$) and $1.49\sqrt{(E/F_y)}$ ($h/t_w \leqslant 35.9$), respectively.

All specimens possessed the same pattern of transverse steel bars, as shown in Fig. 2. Transverse steel bars were composed of closed hoops and crossties. Owing to the presence of the web of the steel shape, a crosstie was formed by two inner ties. As shown in Fig. 3, the longitudinal spacing of transverse steel bars in plastic hinge regions was set at 110 mm, intentionally chosen to be close to the limiting spacing requirements of six times the diameter of