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Experimental study on steel reinforced high-strength concrete columns under cyclic lateral force and constant axial load

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ABSTRACT

This paper presents the results of an experimental study on the seismic behavior of steel reinforced high-strength concrete (SRHC) columns. A total of 21 SRHC columns were tested under simulated earthquake loading conditions, and the major experimental parameters were the axial load level, stirrup arrangement, structural steel details and studs. The effects of these parameters on the behavior of the SRHC columns were analyzed in detail. The test results showed that SRHC columns with multiple stirrups and commonly used structural steel ratios demonstrated excellent seismic behavior and were suitable for use in high-rise buildings in seismic regions. The axial load had a negative effect on the energy dissipation and deformation capacity. Stirrups exhibited little effect on the initial stiffness and lateral force at cover spalling, but had a positive effect on the energy dissipation and deformation capacity. The benefit of structural steel was more obvious when the effective confinement index was larger or the SRHC columns were subjected to a greater axial load. Structural steel also improved the positive effect of the stirrups. It is suggested that multiple stirrups should be adopted in SRHC columns to provide full play to structural steel; in addition, more structural steel should be adopted when significant axial loads are applied to SRHC columns. Studs did not significantly affect the performance of SRHC columns during the early loading stage. However, columns with studs exhibited better energy dissipation and deformation capacity along with slower stiffness degradation.

1. Introduction

High-rise buildings not only save land resources, have more comprehensive architectural functions, but also act as city landmarks and is therefore becoming more and more common in urban areas. The axial loads carried by columns in high-rise buildings typically require larger column sizes, but minimizing the column sizes is desired to increase floor space. The use of high-strength concrete (HSC) and steel-concrete composite structures provides practical solutions to this problem.

HSC is readily available for applications in tall buildings. HSC columns provide increased stiffness and strength for carrying additional loads and offer the benefit of reduced member sizes. However, the main disadvantage of using HSC in columns is that it leads to lower ductility, given the fact that ductility should be treated as critical as strength for columns in seismic regions from the safety point of view. The mechanical properties of HSC columns, including flexural ductility [1–3], basic static mechanical properties [4–9], seismic behavior [10–14], and the effect and design of stirrup confinement [15–20] have been widely studied over the past several decades. Steel-concrete composite columns not only exhibit high levels of strength and stiffness but also possess very good ductility due to their full employment of materials. Composite columns can be made of steel reinforced concrete (SRC) sections or concrete-filled steel tube (CFST) sections. In addition, SRC columns provide higher fire resistance and durability than CFST columns. These advantages have been proven in studies on SRC columns through static tests [21,22], pseudo-static tests [23–25], numerical simulations [26], and theoretical analyses [27,28].

Hence, steel reinforced high strength concrete (SRHC) columns where HSC and SRC are adopted simultaneously, may be a more effective solution to obtain both excellent rigidity and strength (best for large floor spaces) and sufficient seismic ductility. Experimental research has confirmed that the bearing capacity and

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Nomenclature

A_c	area of concrete in a column section
A_g	area of a column section
A_{sh}	gross area of stirrups in one direction
A_s	cross-sectional area of one longitudinal bar, or one leg of hoop
A_{sl}, A_{ss}	gross area of longitudinal bars and cross-sectional area of structural steel
c	dimension of confined concrete core
E_i^j	area surrounded by a cycle j of the ith drift level hysteretic loop
E_{sum}, E_N	cumulative dissipated energy and normalized dissipated energy
f_c, E_c	prism compressive strength and Young's modulus of concrete
f'_h	stress in stirrups at peak strength
f_y, f_{ys}	yielding strength of reinforcement and structural steel
f_u, f_{us}	ultimate strength of reinforcement and structural steel
F_i^{j+}, F_i^{j-}	lateral forces corresponding to Δ_i^{j+} and Δ_i^{j-}, respectively
F_p, F_{sp}	measured peak lateral force and measured lateral force at cover spalling
h, b, t_w, t_f	height, width, web thickness, and flange thickness of structural steel
I_e	effective confinement index of stirrups
K_0	stiffness at a drift level of 0.5%
K_e	geometric coefficient of effectiveness of stirrups
K_i	averaged secant stiffness at the ith drift level
L	height of the column
$M_{n,t}$, $M_{n,c}$	measured and calculated flexural strength
n, n'	axial load ratio defined by P/A_gf_c and P/P_0, respectively
P	applied axial load
P_0	nominal axial load capacity defied by $(A_cf_c + A_{sl}f_y + A_{ss}f_{sy})$
s	stirrup spacing
$\delta\theta_u$	ultimate drift ratio increment
Δ	tip displacement
Δ_i^{j+}, Δ_i^{j-}	maximum tip displacement of the jth cycle at the ith drift level in the pull and push direction, respectively
Δ_u, Δ_y	ultimate and yielding displacement
η_{Ki}	normalized stiffness at the ith drift level
θ_u, μ_Δ	ultimate drift ratio and displacement ductility factor
λ	shear span ratio
ρ_l, ρ_{sv}, ρ_{ss}	longitudinal reinforcement ratio, volumetric ratio of stirrups and structural steel ratio

displacement ductility of SRHC columns are greater than HSC columns, particularly when axial load is large and span-to-depth ratio is small [29]. Because structural steel can resist a percentage of the axial load and moment, and can provide confinement to concrete between its flanges, SRHC columns have significant residual strength [27].

However, there are few works in existing literature that examine the seismic behavior of SRHC columns. Moreover, experimental results by Jia et al. [29] showed that SRHC columns with shear span ratios of $\lambda = 2.75$, axial load levels of $P/P_0 \leqslant 0.35$, stirrup volumetric ratios of $\rho_{sv} = 2.2\%$, and structural steel ratios of $\rho_{ss} = 3.7\%$ had small ultimate drift ratios ($\theta_u \leq 1.6\%$), and most of the columns exhibited low ductility with a flexural-shear failure mode. It could be seen from the experimental results that the unsatisfactory ductility could be due to rectangular stirrups and I-shaped structural steel providing weak confinement to the HSC in all columns. Research on the axial load performance of SRHC columns showed that SRHC columns with multiple stirrups offered a significantly improved ductility factor than columns with rectangular stirrups, even when the volumetric ratios of the stirrups were the same [30].

Therefore, this paper conducts experiments on SRHC columns subjected to cyclic lateral force and constant axial load to investigate the seismic behavior of SRHC columns, and specifically aims to (1) investigate the effects of various factors, particularly stirrup arrangement and structural steel details, on the seismic behavior of SRHC columns; (2) confirm that SRHC columns have sufficient energy dissipation and deformation capacity, even under large axial load impacts, and that they are suitable for use in seismic regions.

2. Experimental program

2.1. Material properties

The high-strength concrete was made with ordinary Portland cement, fly ash, silica fume, coarse aggregate, sand, high-range water-reducing admixture and retarder. The 150 mm × 150 mm × 300 mm prism specimens used to measure concrete strength and Young's modulus were cast and cured with column specimens in the same outdoor conditions. The concrete strength and Young's modulus were measured just before the pseudo-static tests (meaning that the concrete age of column specimens is about 10 months) according to GB/T 50081-2002 [31]. Hot-rolled deformed steel bars and structural steel were used in the column specimens. The +-shaped steel was perpendicularly welded from I-shaped steel. The mechanical properties of steel and concrete are shown in Tables 1 and 2 respectively.

2.2. Specimens and test variables

A total of 21 SRHC columns were tested. All specimens had the same overall geometry, and the dimensions and details of the specimens are shown in Fig. 1. The columns were 200 mm × 200 mm square in cross section, with a height of 600 mm from the point of lateral loading to the top of the footing. The specimens were designed to represent the structural columns of lower stories of high-rise buildings in seismic regions and were fabricated at one-third of full scale. Each specimen had a shear span ratio of $\lambda = 3.0$ to ensure a flexure-dominated deformation mode and represented a 3.6-m (3.6 m = 0.6 m × 3.0 × 2) high column in a typical building, assuming that the point of contra-flexure was located at mid-column height. An RC stub footing with a cross section of 350 mm by 400 mm was cast together with the column, representing a relative rigid member such as a beam-column connection or slab foundation. Each column was reinforced with twelve Φ10-mm longitudinal bars, providing a longitudinal reinforcement ratio of $\rho_l = 2.36\%$. Φ6-mm bars were used as transverse reinforcement. Parameters considered in this experiment included the axial load level, stirrup arrangement, structural steel details and studs, as shown in Table 2.

- Axial load level: three axial load levels were considered, and the axial load level was defined by the axial load ratio ($n = P/A_gf_c$), i.e., the ratio of the applied axial load to the column gross concrete axial load capacity. Compressive force was applied to the top of the column and maintained at 1050, 1600, or 1900 kN.