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Behavior of high-strength concrete slender columns strengthened with steel fibers under concentric axial loading

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HIGHLIGHTS

- The column detailed to ACI 318 exhibited brittle post-peak behavior.
- The closer stirrup had little effect on the load capacity and ductility.
- V_f = 0.75% had little effect in improving the ductility of columns.
- V_f = 1.5% enabled the column to have a ductile post-peak behavior.
- The ACI-ITG equation yielded accurate strength estimations for tested columns.

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ABSTRACT

The deflection demand of slender reinforced concrete columns could be magnified substantially due to its interaction with the axial load, i.e., the P-Delta effect. This study experimentally investigated the behavior of ten slender high-strength concrete columns under concentric axial loads. The experimental variables were the amounts of confinement steel and steel fibers. The adopted high-strength concrete material had an average compressive strength of about 100 MPa. When it was reinforced with steel fibers at a volume fraction of 0.75% or more, it showed the characteristics of high performance fiber reinforced concrete, i.e., tensile strain hardening behavior and multiple narrow cracks. The behavior of the slender high-strength columns was evaluated using various performance measures, such as the failure type, peak strength, dilatation, ductility, steel reinforcement strain, and the P-Delta effect. The results showed that all the columns failed significantly due to the adverse P-Delta effect. The inclusion of steel fibers with a volume fraction of 0.75% or more effectively restrained concrete spalling and crushing and also promoted multiple narrow cracking patterns in the column. In particular, the inclusion of a 1.5% volume fraction of steel fibers enabled the column without steel confinement to exhibit comparable behavior to that of the control specimen that was detailed according to current codes of practice. Furthermore, reasonably accurate equations were suggested for predicting the axial strength of the tested slender, high-strength concrete columns.

1. Introduction

Advancement in concrete material technology has led to the availability and application of high-strength concrete (HSC). While the design of reinforced concrete (RC) columns is benefited by using HSC for the purposes of reducing the cross sectional dimensions, concerns have been raised about the performance of HSC columns. Compared to normal-strength concrete, HSC are more brittle in nature. This causes them to be more vulnerable to spalling and less ductile under seismic loads [1–8]. In addition, the reduced cross sectional dimensions as a result of the employment of HSC increases the potential of the slenderness effect on the column behavior. In other words, the deflection demand of slender HSC columns could be magnified due to its interaction with the axial load, i.e., the P-Delta effect, causing the columns to have reduced load-resistant capacity [9–13].

Inclusion of short, discontinuous fibers is a common strategy for improving the brittleness of HSC. Fibers can bridge across opening cracks and provide post-cracking ductility. When the fibers are sufficiently strong and well bonded to the concrete, fiber reinforced concrete has a high strength retention in the post-cracking stage. As a result, fiber reinforced concrete possesses an enhanced energy absorption capacity compared to conventional concrete materials.

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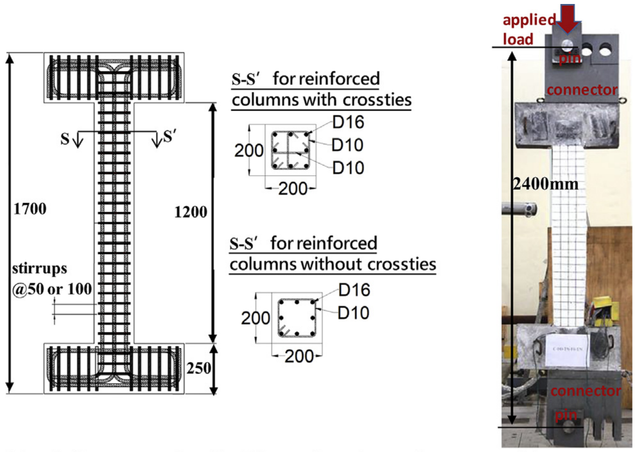
Moreover, studies [14–16] showed that the addition of steel fibers could increase the compressive strength and ductility of HSC. Various studies [17–21] have evaluated the influence of adding fibers on the behavior of HSC columns. Ganesan and Murthy [17] experimentally studied the strength and behavior of short, confined RC columns with and without steel fibers. It was found that the confinement reinforcement could be partially replaced by the addition of short, randomly oriented steel fibers. Numerical models were also proposed to address the enhanced confinement effect due to the inclusion of steel fibers. Paultre et al. [18] demonstrated that the combined use of discrete fibers and transverse steel reinforcement could reduce the amount of confinement reinforcement for HSC columns required by design codes without compromising the structural performance. However, these studies were focused on the behavior of fiber reinforced HSC columns with negligible slenderness effects. The influence of steel fibers on the behavior of slender HSC columns with a significant P-Delta effect remains to be explored.

High performance fiber reinforced concrete (HPFRC) [22–29] is a special type among fiber reinforced concrete materials. It is distinguished from conventional fiber reinforced concrete by its ductile tensile strain hardening behavior accompanied by closely spaced narrow cracks. This tensile performance is endowed by the bridging performance provided by the fibers that effectively link the two sides of opening cracks. The discontinuous short fibers also provide a confining effect similar to that endowed by conventional confinement steel, which can significantly improve the brittle behavior of concrete materials under compression. In addition, the development of HPFRC has resolved issues pertaining to the required large amount of fibers and dispelling workability for conventional fiber reinforced concrete. These enhanced properties of HPFRC have motivated researchers to apply HPFRC in newly built structures and structural strengthening [30–41].

The present study investigated the behavior of slender HSC columns under concentric axial loading. In particular, the potential benefits of using the emerging high-strength HPFRC materials in slender RC columns are explored. The experimental variables include the amounts of confinement steel and short discontinuous fibers. Suitable equations were suggested for predicting the axial strength of slender HSC columns.

2. Column specimens

Ten slender column members were fabricated and tested. The geometries of the members were identical, as shown in Fig. 1. The column member had a test region with dimensions of 200 mm × 200 mm × 1200 mm. Its top and bottom ends had enlarged cross sections to limit the damage in the test region during the test.



(a) reinforcement details (dimensions in mm) (b) test setup

Fig. 1. The design of the concentrically loaded columns.

2.1. Materials

The slender columns were made using HSC with or without fibers. The mix proportions of the HSC material are summarized in Table 1. The components included Type I ordinary Portland cement, silica fume, silica sand (with particle sizes ranging between 0.1 mm and 0.3 mm), quartz powder, polycarboxylate-based superplasticizer, water, and high-strength hooked steel fibers. The employed steel fibers had a length of 30 mm, a diameter of 0.38 mm, an elastic modulus of 201 GPa, and a specified yield strength of 3070 MPa. The HSC material contained a 0%, 0.75%, or 1.5% volume fraction (V_f) of steel fibers. It had a design 28-day compressive strength of 150 MPa. Considering the capacity limit of the employed hydraulic actuator, the columns were tested on the 21st day.

D10 and D16 steel bars with a nominal yield strength of 420 MPa were used for the reinforcement in the columns. Their actual tensile properties as obtained using direct tensile tests are summarized in Table 2.

2.2. Column design

The major experimental variables of the column members included: (1) concrete material and (2) transverse reinforcement. For the transversely reinforced columns, the reinforcement spacing was $s = h/4$ or $h/2$ (i.e., 5 mm or 10 mm), where h is the minimum cross-sectional dimension of the column (20 mm). Two transverse reinforcement configurations were used in the columns. The first configuration was a D10(#3) perimeter hoop without any crosstie. The other configuration was a D10(#3) perimeter hoop with a D10 (#3) crosstie having 135-degree seismic hooks each way, which allowed every longitudinal bar around the perimeter of the column core to be laterally supported by either the corner of a hoop or a seismic hook, as required by ACI 318 [42] for f'_c larger than 69 MPa. The notations and reinforcement details of the column members are summarized in Table 3. The numbers following “H” and “T” are the spacing of the perimeter hoops and crossties, respectively, except a “0” was used to represent none. The number following “F” denotes the volume fraction of the steel fibers. For example, “H0T0-F75” denotes the column without hoops and ties and having steel fibers with a 0.75% volume fraction, and “H10T0-F150” denotes the column having 10 mm-spaced perimeter hoops, without crossties, and having steel fibers with a 1.5% volume fraction. The H5T5-F0 column, which was designed conforming to ACI 318 [42], was employed as the control specimen in this study. Fig. 2 shows the preparation of the column specimens at different stages.

3. Test instrumentation and load protocol

3.1. Material tensile and compressive tests

The compressive strength, f'_c, of the concrete materials was obtained by carrying out compressive tests conforming to ASTM C39 on cylinder specimens with dimensions of 75 mm × 150 mm. In addition, direct tensile tests on dog-bone specimens were performed to identify the tensile properties of the concrete materials. The configuration, dimensions, and test setup of the dog-bone specimen are presented in Fig. 3. During the tensile test, the elongation of the specimen within a gauge length of 160 mm was monitored using two linear variable displacement transducers