Engineering Structures 172 (2018) 497–507

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Axial compressive behavior of concrete columns with grade 600 MPa reinforcing bars

Yizhu Li, Shuangyin Cao*, Hang Liang, Xiangyong Ni, Denghu Jing

Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing, PR China
School of Civil Engineering, Southeast University, Nanjing 210096, PR China

ARTICLE INFO

Keywords:
Axial loading
Columns
Grade 600 MPa reinforcing bar
Post-peak deformability
Toughness

ABSTRACT

An experimental study was performed to investigate the axial compressive behavior of concrete columns with Grade 600 MPa reinforcing bars. Nine large-scale concrete square columns were constructed and tested under pure axial loading. The effects of Grade 600 MPa transverse reinforcement with two different configurations (Type A and B) and amounts were evaluated. The behavior of columns was characterized by sudden spalling of concrete cover and ductility failure for well-confined columns, which was dominated by effective confinement index ($k_e\rho_{sh}f_{yh}/f_c'$). Columns confined by Grade 600 MPa transverse reinforcement exhibited the better performance in terms of strength, post-peak deformability, and toughness when compared with columns reinforced with conventional steel. The benefit of using Grade 600 MPa longitudinal bars on the axial load capacity of columns is limited, but it is beneficial to improve the post-peak deformability and toughness of columns with Type B configuration. A design expression is proposed for the amount of seismic confinement to ensure ductility behavior for columns, based on the effective confinement index.

1. Introduction

The use of high-strength reinforcing bars in large span, overloaded and high-rise buildings can reduce the concrete member size, increase building usable area, make the structure design more flexible, and also can greatly reduce the steel congestion and construction costs. In addition, inelastic deformability of RC columns is essential for overall stability of structures in order to sustain strong earthquakes. Well inelastic deformability of columns can be achieved through improved confinement of the core concrete. It is now well documented that the desired ductility can be attained for columns by providing high-strength transverse reinforcement [1–4].

Recently, the gradual development of reinforcement technology has resulted in high-strength steel bars with nominal yield strength of 600 MPa. The new developed Grade 600 MPa reinforcing bars have a linear preyield behavior, a well-defined yield plateau and relatively high ductility. The measured stress-strain curves of Grade 600 MPa and 400 MPa reinforcing bars are compared in Fig. 1. The tensile-to-yield strength ratio of Grade 600 MPa steel bars was larger than that of Grade 400 MPa steel bars, while the rupture elongation of Grade 600 MPa steel bars is approximately two-third the elongation of Grade 400 MPa steel bars. Therefore, the Grade 600 MPa reinforcing bars with varying mechanical properties have a significant impact on the behavior of concrete members.

Many researchers have carried out the experimental study on the behavior of concrete members with high-strength reinforcing bars, including beams [5–8], columns [9–17], walls [18–20] and beam-column joints [21–23]. Rautenberg et al. [9,10] and Link [11] tested concrete columns reinforced with Grade 80 (550 MPa) and Grade 100 (690 MPa) steel bars under cyclic loading and concluded that the columns with high-strength steel exhibited similar flexural strength, similar drift capacity, similar curvature ductility, but lower energy dissipation when compared with columns with conventional steel. Su et al. [12–14] carried out cyclic loading tests on the square and circular concrete columns with Grade 600 MPa reinforcing bars and concluded that columns reinforced with Grade 600 MPa reinforcing bar have similar seismic performance when 600 MPa steel bars replace normal-strength steel bars with equal steel strength replacement. And they also proposed a simplified buckling model for Grade 600 MPa steel bar that reflect the influential factors of bar buckling. Hwang et al. [21] performed an experimental study to evaluate the seismic behavior of beam-column joints using Grade 600 MPa bars and mentioned that the load-carrying capacity and maximum deformation of joint with 600 MPa bars were close to those of the specimen with 400 MPa bars. On the hand, the energy dissipation capacity of the specimen with 600 MPa bars decreased by a maximum of 25% due to the increased bond-slip at

* Corresponding author at: Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing, PR China.
E-mail address: 101000873@seu.edu.cn (S. Cao).

https://doi.org/10.1016/j.engstruct.2018.06.047
Received 12 January 2018; Accepted 12 June 2018

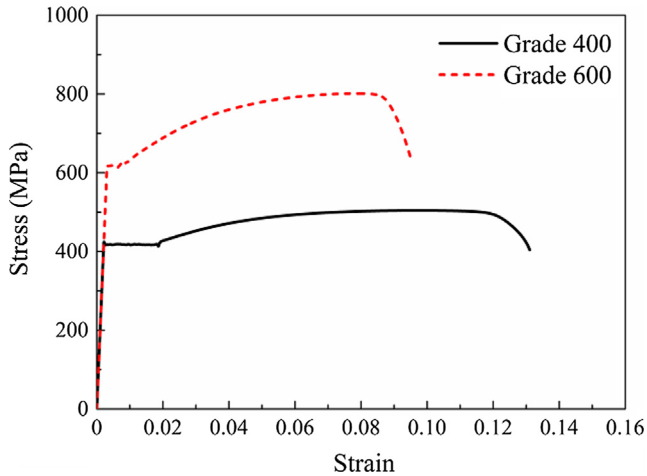

Fig. 1. Measured stress-strain curves of Grade 600 MPa and 400 MPa reinforcing bars.

the joints. In addition, Chen and Yi [24] conducted a series of variable amplitude cyclic loading tests on the Grade 600 MPa reinforcing bars and found that Grade 600 MPa steel bars exhibited brittle failure characteristics.

As shown, most of the previous studies of columns have focused on the effect of Grade 600 MPa reinforcing bar on seismic behavior. Limited experimental and analytical studies have been conducted to understand the axial compressive behavior of concrete columns with Grade 600 MPa reinforcing bars (including transverse reinforcement and longitudinal bar). This study focuses on the behavior of concrete columns with Grade 600 MPa reinforcing bars under axial loading. Nine large-scale concrete square columns were fabricated and tested to investigate the effect of using Grade 600 MPa reinforcing bars. The investigated parameters included yield strength of reinforcing bar and high-strength transverse reinforcement configuration and amount. In addition, this paper also investigated the required amount of seismic confinement reinforcement to ensure ductility behavior of columns.

2. Experimental program

2.1. Test specimens

The specimens tested in this investigation consisted of a total of nine 350 × 350 × 1000 mm RC columns. Each column was divided into two parts: a 600 mm high central test region; and two end regions (each 200 mm high) heavily reinforced by denser stirrups to avoid unexpected failure occurring there. And the two end regions were further strengthened using three layers of carbon fiber-reinforced polymer (CFRP) wrap before the specimens were tested. All columns had cover concrete of 20 mm, leading to a constant ratio of core concrete area to the gross area of 0.78. Two configurations of transverse reinforcement, Type A and B, were considered in the test. The Type A configuration was confined by outer square hoops and inner diamond-shaped hoops with 135-degree hooks and $6d_b$ bar extensions. The Type B configuration was confined by outer square hoops as well as inner rectangular hoops in each direction with 135-degree hooks and $6d_b$ bar extensions. Type A columns were fabricated using 8-D20 longitudinal bars except column AC4 with 8-D16, resulting in a longitudinal reinforcement ratio of 2.05% and 1.31%, respectively. All the Type B columns were fabricated with 12-D16 longitudinal bars, resulting in a longitudinal reinforcement ratio of 1.97%. Two levels of transverse reinforcement spacing in each type column – 60 mm and 90 mm for Type A columns, 70 mm and 105 mm for Type B columns – were studied with transverse reinforcement ratio (ρ_{sh}) of 1.91% and 1.28%, respectively. The reinforcement and cross-sectional details of columns are shown in Fig. 2, and Table 1 gives the test design details.

2.2. Test variables

The test reported in this paper was designed to investigate two variables that affect the axial load behavior and confinement of concrete columns: (1) the effects of using Grade 600 MPa transverse reinforcement in different configurations and amounts; (2) the effects of using Grade 600 MPa longitudinal bars. Type A and B configurations of transverse reinforcement were considered in each pair of test specimens to evaluate their confinement effectiveness. The transverse reinforcement ratio ranged from 1.28% to 1.91%, and the ratio of transverse reinforcement provided in each column to the required amount of ACI 318-14 [25] ranged from 1.15 to 1.72. The measured yield strength of transverse reinforcement was 476 MPa for normal-strength reinforcement and 642 MPa for Grade 600 MPa reinforcing bar (refer to Tables 1 and 2). The measured yield strength of normal-strength longitudinal bars was 435 MPa on average, ranging from 424 to 446 MPa, and the measured yield strength of Grade 600 MPa longitudinal bars was 617 MPa.

Columns AC1 and BC1 represent columns confined by normal-strength transverse reinforcement and both contained 1.91% of transverse reinforcement, corresponding to approximately 127% of the transverse reinforcement amounts required by the provisions of ACI 318-14 [25]. D8 steel bars with a vertical spacing of 60 and 70 mm were used for the transverse reinforcement for Columns AC1 and BC1, respectively. Eight D20 reinforcements were used for the longitudinal bars for Column AC1, while twelve D16 reinforcements were used for longitudinal bars for Column BC1.

Columns AC2 and BC2 were confined by D8 Grade 600 MPa transverse reinforcement and contained the same amounts of transverse reinforcement (1.91%) as comparison Column AC1 and BC1. The Grade 600 MPa transverse reinforcement amount of 1.91% resulted in 172% of the required amount of ACI 318-14 [25]. These columns were fabricated using the same geometry and strength as the aforementioned longitudinal bars for each type of configuration.

Columns AC3 and BC3 represent columns reinforced by Grade 600 MPa transverse reinforcement but with a lower amount (1.28%) compared with the previous four columns, resulting in 115% of the transverse reinforcement amount required by AC1 318-14 [25]. The comparison of the response of these columns provides an understanding of the beneficial effects of the use of Grade 600 MPa transverse reinforcement for reducing steel congestion in concrete columns. These columns were constructed using the same aforementioned longitudinal bars for each type column. D8 Grade 600 MPa reinforcing bars with a vertical spacing of 90 mm and 105 mm were used for the transverse reinforcement for Columns AC3 and BC3, respectively.

Columns BC4 and BC5 were detailed with same geometry and transverse reinforcement as Columns BC3 and BC2, respectively, but only differed in the yield strength of longitudinal bars. Columns BC4 and BC5 were constructed with twelve D16 Grade 600 MPa longitudinal bars. Column AC4 was constructed using the same geometry and transverse reinforcement as Column AC2 but with a lower amount and higher yield strength of longitudinal bars. Eight D16 Grade 600 MPa reinforcements were used for longitudinal bars for Column AC4, resulting in the longitudinal bar ratio of 1.31%.

2.3. Material properties

Concrete – The nine columns in this study were cast using one batch concrete mixes with specified design concrete cube strength of 50 MPa. The materials consisted of Type II Portland Cement with 28-day nominal compressive strength grade of 52.5 MPa, silica sand, coarse aggregate (maximum size of 16 mm), tap-water of mixing, fly ash and mineral powder to maintain flowability for casting. The sand-aggregate ratio was 36% and the water-cementitious materials ratio of 0.32 was