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Effects of cross section size and transverse rebar on the behavior of short squared RC columns under axial compression

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ABSTRACT

The paper reports the results of a series of tests of geometrically similar stocky reinforced concrete (RC) columns having different sizes with a ratio of 1:1.5:2.25. The effects of stirrup ratio, tie arrangement type and yield strength of stirrups on the failure and size effect of RC columns under axial compression were explored. Moreover, a 3D meso-scale numerical method for the simulation of failure of RC members was developed. The test observations demonstrate the existence of size effect in larger-sized RC columns, and the failure is governed by fracture. With increasing the stirrup ratio, the number of stirrups leg and yield strength of stirrups could make the enhancement of nominal strength and improvement of ductility capacity of RC columns. The RC columns with a lower stirrups ratio, a smaller number of tie legs, and a lower yield strength of stirrups present much more brittle failure, exhibiting much stronger size effect. The test data illustrates that the nominal compressive strengths are consistent with the size effect law (SEL) proposed by Bažant. Moreover, good agreements between the simulation results and the test observations illustrate the reasonability of the developed meso-scale simulation approach.

1. Introduction

Reinforced concrete (RC) has been widely utilized in various engineering structures, e.g. high-rise buildings, underground and mountain tunnels, cross-sea bridges, off-shore platforms, gravity and arch dams, giant nuclear power plants as well as protective containment of nuclear reactors. The structural dimensions of these engineering structures are becoming larger and larger, making the safety of these large-sized engineering structures become one of the most concerned topics. The so-called *size effect*, which is known as independence of the nominal strength and the brittleness on structural size, turns out to be a vital issue for the design of these larger-sized RC structures. Therefore, the knowledge on the failure mechanism and mechanical properties of RC members is of great importance for the design of RC structures, especially for the large-sized RC structures.

The structural bearing capacity predicted by any deterministic strength theory involving the elastic, plastic or elastoplastic strength criterion, does not present any size effect. In reality, it has been increasingly being theoretically and experimentally believed that the size effect exists in concrete materials [1–7]. In addition, numerous experimental observations [6–18] have indicated that the size effect may also exist in the failure of RC members, including RC beams, RC columns and RC beam-to-column connections. These theoretical and experimental efforts contribute to the understanding of size effect in concrete materials and concrete structures. Nevertheless, because of the limitations of the test conditions and the economic factors, the efforts on the failure mechanism and mechanical behavior of large(r)-sized RC members are still insufficient and not systematic [19].

1.1. Size effect in RC columns

RC columns, as one of the most important support components in the architectural structures, whose mechanical behavior has been studied widely. So far, lots of contributions have been conducted to explore the failure behavior and size effect of RC columns, e.g. in the publications of [9,12–15,20–23]. These experimental and numerical efforts have demonstrated the presence of size effect in the nominal compressive strength of RC columns under axial compressive load. Essentially, for RC columns, the size effect on the nominal strength should be affected by (1) the inherent features of concrete and steel bars, and (2) the complex mutual effects between steel bars and the surrounding concretes [24]. In the above test efforts, the effects of slenderness

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ratio, stirrup ratio, stirrup spacing and strength grade of concrete on the failure behavior and size effect of RC columns have been systemically investigated. Moreover, the mutual effects between steel bars and surrounding concretes, including the failure of bond (slip or separation), have also been deeply explored on the size effect in RC columns, such as in [9,12–14,25]. However, the structural sizes of the tested RC columns were much smaller than the practical ones. For instance, the maximum cross-sectional widths of the RC columns tested in [9,12–15] were respectively 50.8 mm, 150 mm and 300 mm.

As mentioned previously, large-sized RC columns have now been applied extensively in high-rise buildings and cross-sea bridges, etc. The corresponding cross-sectional sizes of the RC columns utilized in these engineering structures are far greater than the available tested ones. However, it remains unknown for the possibility of existence of size effect in large-sized RC columns. This, inevitably, leads to a very uncertain or even unsafe design for these engineering structures.

Recently, Li et al. [24] have conducted a series of tests on the failure behavior and size effect of normal and moderate high-strength RC columns subjected to axial compressive loading, in which the maximum cross-sectional sizes of the tested columns were 800 mm × 800 mm. The test observations, as expected theoretically, have indicated that the RC columns exhibit a strong size effect on the nominal compressive strength.

To discover the influence of loading patterns, Jin et al. [26] tested the mechanical behavior and size effect of reinforced high-strength concrete columns under cyclic axial compression. The test observations have indicated that compared with the one under monotonic compressive loading, the failure of the RC columns under cyclic axial loading turns out to be more brittle due to the cyclic fatigue characteristics. This makes a more pounced size effect in the columns under cyclic axial compression. Moreover, the effect of loading eccentricity was also studied experimentally on the failure behavior and size effect of RC columns in the work [19].

In the previous work [24], the size effect of RC columns having different stirrup ratios (0, 0.65%, 1.2% and 1.31%), slenderness ratios ($\lambda = 3$ and 4) and strength grades of concrete was explored. In the tests, the maximum cross-sectional width of the tested columns was 800 mm. The test observations have demonstrated the existence of size effect in large(r)-sized RC columns. The efforts should be considered a valid contribution to understand the size effect. However, the confinement effects generated by transversal reinforcement on the size effect in RC columns was not systematically examined in the previous work.

1.2. Objective of the present study

In this work, the tests on the failure behavior of axial-loaded stocky RC columns were conducted for two main objectives. One was to investigate the size effect in axially-loaded larger-sized RC columns, and the other one was to systemically discover the influences of stirrups ratio, tie arrangement type and yield strength of transverse bars on the size effect of RC columns.

In this study, a total of 26 RC columns having different structural sizes, different stirrup ratios (i.e. 1.26% and 2.89%), different tie arrangement types and different yield strengths of transverse reinforcement were tested. The cross-sectional width of the columns varied from 267 mm to 600 mm, and the column length ranged from 800 mm to 1800 mm. The slenderness ratio of all columns was 3. Based on the test results, the failure behavior of the RC columns was explored, and the corresponding size effect on the nominal compressive strength was analyzed.

Compared with the previous work of [24], the utilized stirrup amount was obviously increased. Moreover, the effects of tie arrangement types and yield strengths of stirrups were explored. Therefore, the present study is the complementarity of the previous work. Moreover, the tests can also be treated as an addition of the earlier efforts [9–10,12–16].

2. Experimental program

2.1. Material properties

The mixture proportions of the concrete utilized in the present tests are given in Table 1. Medium sands are considered as the fine aggregate (i.e. the average diameter is less than 5 mm), and crushed pebble stones as the coarse aggregate (i.e. the average diameter ranges from 5 mm to 30 mm). It is to be noted that the concrete mixture components were not scaled to the characteristic dimension, and the maximum diameter of the large coarse aggregate particles (crushed pebble stones) was about 25 mm for all columns. Actually, the focus of this study is on the size effect of components rather than the one in materials. As known, scaling the size or distribution of aggregates may complicate the evaluation of the test results and prevent isolating the structural size effect from other influences [9,24]. In addition, casting from the same batch of continually mixed concretes would make the mechanical behavior of the concrete samples more stable. The mass density of the utilized concrete was 2434 kg/m^3 and the water-to-cement ratio w/c was 0.4. The slump of the concrete utilized was 160 mm–180 mm. The corresponding mean values of 28 days splitting tensile and compressive strengths of standard plain concrete cube samples, sized of 150 mm × 150 mm × 150 mm, were measured as 3.0 MPa and 42.8 MPa, respectively. The measured modulus of elasticity of the concrete utilized was 34.8 GPa. Herein, the tensile strength was measured by splitting tensile tests introduced by the code of "Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T 50081-2002)" of China [27].

Moreover, the mechanical parameters for aggregate particles and mortar matrix (mixture of fine aggregates and water) were also measured. For aggregates, the modulus of elasticity is 70.1 GPa, and the Poisson's ratio is 0.2. For mortar matrix, the modulus of elasticity is 30.8 GPa, the Poisson's ratio is 0.2, and the uniaxial tensile and compressive strengths are respectively 3.8 MPa and 45.3 MPa.

To explore the effect of yield strength of stirrups on the failure of RC columns, two types of steel rebar were used, as summarized in Table 2. The "HRB" (denoted as ⏀) is the shortened form of "Hot-rolled Ribbed-steel Bar". The "HRB400" means that the standard value of yield strength is about 400 MPa, and the yield strength of the high(er)-strength steel (denoted as ϕ^{PM}) is 1044 MPa.

The steel type HRB400 was used as longitudinal steel rebar for all columns. The measured physical and mechanical properties of the steel bars adopted in the tests, including the diameter, yield strength, ultimate strength, yield strain and modulus of elasticity, are provided in Table 2.

2.2. Test specimens

A total of 26 geometrically-similar RC columns were tested. The design principles satisfy that: 1) all columns are geometrically similar, and 2) the layout of the reinforcement are geometrically similar. The corresponding geometric configuration and reinforcement layout of the 26 RC columns adopted in the tests are presented in Fig. 1. The cross-sectional width of the tested columns ranged from 267 mm to 600 mm, and the height changed from 800 mm to 1800 mm. The slenderness λ of all columns was 3. The longitudinal reinforcement arranged in all specimens was mainly used for fixing