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# Size effect on axial stress-strain behavior of CFRP-confined square concrete columns

D.Y. Wang [a,b], Z.Y. Wang [a,b,*], S.T. Smith [c], T. Yu [d]

[a] Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin, China
[b] School of Civil Engineering, Harbin Institute of Technology, Harbin, China
[c] School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia
[d] Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW, Australia

## HIGHLIGHTS

- Axial stress-strain behavior of FRP-confined square concrete columns.
- Influence of size effect on column behavior and FRP effective strain.
- Experimental investigation and model development for FRP-confined concrete columns.
- Calibration of effective strain model considering size in FRP-confined columns.

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## ABSTRACT

Research published on the axial compressive behavior of fibre-reinforced polymer (FRP)-confined concrete columns has been generally based on small-sized specimens. There have been limited studies published on large-sized columns and there have also been limited studies on the validity of upscaling results obtained from small-sized specimens. On account of such knowledge gap, this paper presents the test results of 23 carbon FRP-confined square concrete columns of varying sizes subjected to monotonic axial compression. The specimens were sorted into 10 groups based on (i) specimen size, (ii) theoretical lateral FRP confining pressure, (iii) number of layers of FRP wrap, and (iv) inclusion and exclusion of internal steel reinforcement. In each group, the specimens consisted of different cross-sectional sizes but the same theoretical lateral confining pressure. The experimental results showed that specimen size had no significant effect on the axial stress-strain behavior of FRP-confined medium- and small-sized columns (i.e. sections defined herein equal to and less than 300 mm in width). The axial stress-strain responses exhibited differences as the specimen size increased. This was especially the case for FRP-confined large-sized columns (i.e. sections defined herein equal to and larger than 350 mm in width). The rupture strain of the FRP wrap at the corner regions is proposed to be defined as the effective lateral rupture strain of FRP, and this strain was shown to decrease with an increase of specimen size. Based on the test results, a modified FRP effective strain factor model considering the influence of size effect is proposed.



## 1. Introduction

The axial compressive behavior of fibre-reinforced polymer (FRP)-confined concrete has received significant attention over the last two decades. As a result, it is now well established that the confinement of concrete with FRP composites can substantially enhance concrete strength and ductility. A number of experimental and theoretical investigations have been conducted to date on FRP-confined concrete columns [1–13]. The majority of such studies have focused on the axial compressive performance of FRP-confined small-sized cylinders and prisms. In cases, axial stress-strain models have been developed and such models are very important for the design of FRP-strengthened structures. Small specimens, as opposed to large-sized specimens, are widely used in tests since they are relatively easy to handle, economical, and typically require more readily available test equipment of lesser size and capacity. However, the validity of extrapolating results

* Corresponding author at: Room 520, School of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China.
*E-mail addresses:* daiyuwang@hit.edu.cn (D.Y. Wang), zhenyuwang@hit.edu.cn (Z.Y. Wang), scott.smith@scu.edu.au (S.T. Smith), taoy@uow.edu.au (T. Yu).

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from small-sized test specimens as well as the proposed models arising to more realistic larger-sized columns has been largely devoid of research. Moreover, design codes for concrete structures retrofitted with FRP composites [14,15] do not consider size effect. In this paper, large-size, medium-size, small-size and very small-size columns are defined by cross-sectional dimensions of about 350 mm (and greater), 250 mm, 100 mm, and 50 mm, respectively. These sizes are based on comparison with real structures by the authors and they have also been defined in a similar manner in other studies as well [16–18].

Limited studies have been conducted on the influence of cross-sectional size on the axial compressive behavior of FRP-confined concrete columns [16–25]. For FRP-confined circular columns, most of the existing studies indicated that the cross-sectional size has no obvious influence on the axial stress-strain behavior. For example, Thériault et al. [16] tested FRP-confined circular columns with three different diameters and two different slenderness ratios. The test results indicated that no significant size effect was observed for medium-(152 mm in diameter) and large-sized (304 mm in diameter) columns. Size effects were evident only in very small specimens of 51 mm in diameter. Carey and Harries [19] investigated the axial behavior of FRP-confined circular columns with similar confining stiffness but different sizes. The results showed that the column sizes had no significant influence on the axial stress-strain behavior. Zhu et al.'s [20] experimental studies on the axial compression behavior of concrete-filled FRP tubes showed that specimen size did not appear to influence either the confinement or the overall axial compression response. In another study, Elsanadedy et al. [17] investigated experimentally and numerically the influence of size effect on FRP-wrapped concrete circular columns. Thirty-seven concrete cylinders with three different sizes (50, 100 and 150 mm in diameter) were tested. The test and numerical results showed the effect of specimen size on FRP-confined circular concrete columns to be insignificant. Nevertheless, Pessiki et al. [21] indicated that the stiffness of the FRP confinement in specimens of small-size may be significantly greater than larger-sized columns that would be expected in practice. Cross-section geometry therefore significantly influenced the axial behavior of FRP jacketed specimens.

Studies on FRP-confined noncircular columns, however, produced results opposite to circular columns in that the cross-sectional size significantly influenced the axial compressive behavior. For example, Masia et al. [22] tested the axial compressive behavior of 30 square columns with 3 different cross-sectional sizes (100 mm, 125 mm and 150 mm). The test results indicated that the effectiveness of the FRP confinement reduced with increasing cross-sectional size. However, in this study the corner radius was 25 mm for all the specimens. In this case, the shape factor of small-sized columns was larger than that of larger-sized columns. Note that the shape factor refers to the ratio of the effectively confined concrete to the total cross-sectional area of concrete. Consequently, the results in this study were influenced not only by cross-sectional size but also the corner radius ($r_c$). The conclusions of the influence of size effect are therefore questionable. Rocca [23] tested larger-sized FRP-confined square RC columns with cross-sectional widths ($b$) of 324 mm, 457 mm, 648 mm and 914 mm. The test results showed clear differences in the axial stress-strain behavior between smaller and larger columns. Toutanji et al. [18] tested three field-size square (355 × 355 mm) and rectangular (250 × 500 mm) columns under axial compression. Based on test results, existing ultimate axial strength and stress-strain models which have mostly been developed for small-scale specimens were evaluated. The comparison indicated that some models failed to adequately characterize the axial stress-strain response of the tested large-scale columns. Wang and Wu [24] studied experimentally the size effect of short concrete columns confined with aramid FRP (AFRP). The test results demonstrated that specimen size had significant effect on the strength of confined columns, but it had lesser effect on the axial stress-strain curves. It also had a slight effect on the failure modes. Based on the test results, a sized-dependent stress model was proposed by modifying Bažant's size-effect law. Finally, Wang et al. [25] investigated the axial stress-strain behavior of carbon FRP (CFRP)-confined larger-sized concrete square columns with two specimen sizes but the same ratio of $r_c/b$. Their test results showed that the effective lateral confinement of CFRP was significantly influenced by the cross-sectional dimensions of the confined columns. In summary, existing studies have mostly confirmed that cross-sectional size has no real apparent influence on the behavior of FRP-confined circular columns, but it does have significant effect on FRP-confined noncircular columns. As findings to date are not that conclusive, further research on the influence of size effect on FRP-confined noncircular columns is warranted.

This paper presents an experimental study on CFRP-confined square columns with different cross-sectional sizes subjected to monotonic axial compression. A total of 23 unreinforced and reinforced concrete columns divided into 10 groups were fabricated and tested. Five of the groups consisted of plain concrete columns while the other five groups consisted of concrete columns reinforced with steel reinforcement. In each group, the specimens consisted of different cross-sectional sizes but the same theoretical lateral confining pressure calculated according to ACI 440.2R-08 [14]. The test results are used to confirm whether size effect exists in FRP-confined square columns, especially in larger-sized columns. A new FRP effective strain factor model for FRP-confined square concrete columns, considering the influence of cross-sectional size, is finally proposed.

## 2. Experimental program

### 2.1. Test specimens and materials

The test specimens consisted of seven different cross-sectional sizes which varied from 100 mm to 400 mm, as shown in Fig. 1. All specimens, however, contained the same height to cross-sectional width ratio ($H/b$) of 3.0 in order to ensure the influence of slenderness ratio was not a test variable. Existing studies have demonstrated that the confinement efficiency of wrapped FRP was significantly influenced by the corner radii of noncircular columns [26]. However, on account of the position of the internal steel reinforcement, the corner radius cannot be rounded as large as ideally desired. To ensure the influence of corner radius was the same for all the specimens, the corner radius to width ratio ($r_c/b$) was set to be constant value of 0.15 for all specimens. The test specimens were divided into 10 groups. Five of the groups (i.e. groups GA1 to GA5) consisted of plain concrete columns while the remaining five groups (i.e. groups GB1 to GB5) consisted of concrete columns reinforced with steel reinforcing bars. The specimens of each group contained different cross-sectional sizes but the same theoretical lateral FRP confining pressure according to ACI 440.2R-08 [14]. For the steel reinforced specimens, approximately the same longitudinal and lateral steel reinforcement ratios were maintained.

The lateral FRP confining pressure model adopted by ACI 440.2R-08 [14] is expressed as:

$$f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D} \tag{1}$$

where $f_l$ = lateral confining pressure of FRP, $E_f$ = elastic modulus of FRP, $n$ = number of layers of fibre sheet, $t_f$ = thickness of one ply of FRP wrap, $\varepsilon_{fe}$ = effective lateral strain of FRP at failure, and $D$ = diameter of circular column. For noncircular cross sections, $f_l$ in Eq. (1) corresponds to the lateral confining pressure of an equivalent circular cross section with diameter $D$ equal to the length of the diagonal of a rectangular cross section as follows

$$D = \sqrt{b^2 + h^2} \tag{2}$$

where $b$ = section width and $h$ = depth of column section. As a result, the equivalent diameter of square columns is equal to $\sqrt{2}b$. For the reinforced concrete columns investigated, the longitudinal steel reinforcement ratio and the volumetric ratio of the hoop reinforcement were approximately equal to 1.5% and 0.4%, respectively. In addition, the hoop reinforcements were terminated inside the core concrete using a 90° hook in order to simulate non-ductile RC columns. The reinforcement details of each group are illustrated in Fig. 1.