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Experimental and numerical investigation of size effects in FRP-wrapped concrete columns

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ABSTRACT

Some FRP confinement models available in the literature are based on standard cylindrical specimens and others are based on mixed sizes of cylindrical specimens. The accuracy of the latter models is questionable, as it depends on the percentage of increase in strength between unconfined and FRP-confined specimens and on the ratio of strength increase among the different sizes of specimens. The question which can be raised here is: is there a need to introduce a size factor for the test results which are based on non-standard sizes of cylindrical specimens before using them in developing analytical models for FRP-confined concrete? The output of this study answers this important question. Thirty-seven concrete cylinders with three different sizes were experimentally tested. Of these, 13 cylinders were control specimens, to be used as baseline for comparison, whereas the remaining 24 cylinders were wrapped with layers of CFRP jacket. Studied parameters were specimen size and confinement stress ratio. In addition to the experimental investigation, non-linear finite element analysis was also carried out using LS-DYNA software. The predictions of the numerical finite element models were found to agree well with the experimental results of the specimens tested in this study in addition to others selected from the literature. Based on this validation, the effect of specimen size on FRP-confined concrete cylinders was further investigated numerically taking into consideration various confinement ratios and cylinder sizes. The results show that the effect of specimen size on FRP-confined concrete is insignificant.

1. Introduction

During the early 90s, most of the external confinement techniques for columns included increasing the section by either constructing an additional concrete cage or by installing grout-injected steel jackets. Both methods are labor intensive and present difficulties at the site. Presently, fiber-reinforced polymer (FRP) confinement of reinforced concrete columns has been shown to be a very effective technique for structural enhancement. FRP's also present various advantages such as, light weight, high confinement strength, high strength-to-weight ratio, easier installation and maintenance and also durable. FRP-wrapping, prefabricated laminate jacketing and filament winding can substantially enhance the axial compressive strength and ductility of concrete columns due to lateral confinement as demonstrated by numerous investigators, e.g. [1–3]. Studies have also shown that FRP-confined concrete behaves differently from steel-confined concrete [4], so design recommendations developed for steel-confined concrete columns (or cylinders) cannot be applied to FRP-confined columns despite the apparent similarity between these two types of columns or cylinders. Toutanji and Balagurce [5] investigated effectiveness of FRP wrapping for strengthening plain concrete cylinders. Two layers of CFRP or GFRP wrap were applied to the cylinder. They observed 200% and 100% increase in the compressive strength with CFRP and GFRP wraps, respectively. Parvin and Jamwal [6] investigated the behavior of small-scale FRP-wrapped concrete cylinders under uniaxial compressive loading using non-linear finite element analysis. They considered two parameters for the numerical study: the FRP wrap thickness, and the ply configuration. The finite element analysis results showed substantial increase in the axial compressive strength and ductility of the FRP-confined concrete cylinders as compared to the unconfined ones. The increase in wrap thickness also resulted in enhancement of axial strength and ductility of the concrete cylinders. Berthet et al. [7] presented the results of an experimental investigation concerning the compressive behavior of short concrete columns externally confined by carbon and E-glass FRP jackets. The results showed that external confinement can significantly improve the ultimate strength and ductility of the specimens. Lam and Teng [8] proposed a design-oriented stress–strain model for concrete confined by FRP wraps with fibers only or predominantly in the hoop direction. The model is based on a careful interpretation of existing test data and observations. The predictions of the model

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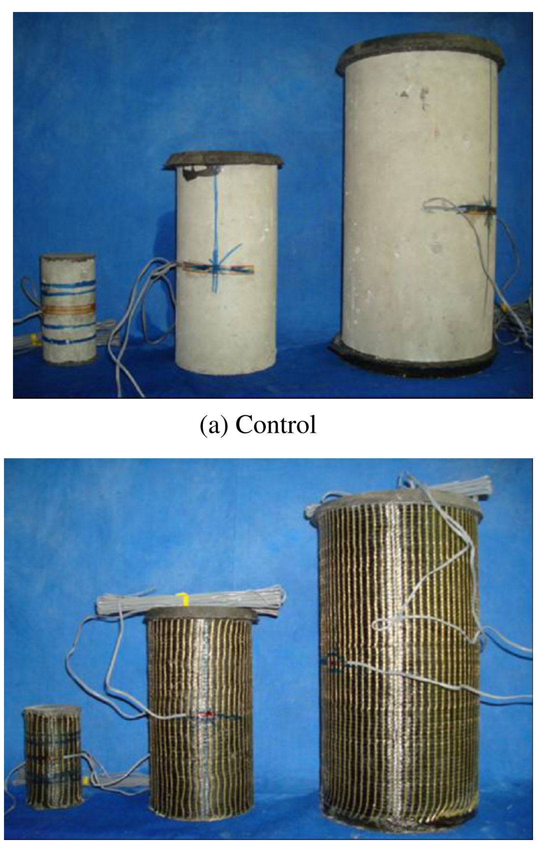
Table 1
Test matrix used in this study.

Specimen designation	Diameter, D (mm)	Height, H (mm)	No. of CFRP layers	Thickness of CFRP jacket, t_j (mm)	Confinement ratio $\left(\rho_j = \frac{4t_j}{D}\right)$	No. of specimens
U-50	50	100	–	–	0	4
U-100	100	200	–	–	0	4
U-150	150	300	–	–	0	5
W1-50	50	100	1	1	0.08	4
W1-100	100	200	1	1	0.04	5
W2-100	100	200	2	2	0.08	4
W1-150	150	300	1	1	0.027	5
W2-150	150	300	2	2	0.053	2
W3-150	150	300	3	3	0.08	4
Total no. of specimens						37

Table 2
Proportions of ingredients used for concrete mix.

Ingredients	Quantity (for 1 m^3)
Cement (type 1)	350 kg
Silica sand	585 kg
Washed sand	195 kg
10 mm aggregate (3/8″)	315 kg
20 mm aggregate (3/4″)	735 kg
Free water	175 kg
Absolute water	3.82
Admixture	0.6% by weight of cement



(a) Control

(b) CFRP-wrapped

Fig. 1. Test specimens.

were found to agree well with test data. Almusallam [9] conducted a comprehensive experimental program which involved 54 plain concrete cylinders with varying compressive strength wrapped with E-glass/epoxy fiber reinforced polymer (GFRP) jackets and subjected to uniaxial compressive loads. The influence of number of composite plies (i.e. composite thickness) and concrete compressive strength on the behavior of the GFRP-confined cylinders was investigated. The results of this study showed that: (i) compressive strength and ductility of the concrete cylinders increases with number of composite layers; and (ii) effect of confinement is substantial for normal strength concrete and marginal for high-strength concrete. A semi-empirical theoretical model was also developed in order to predict stress–strain relationship of GFRP-confined concrete cylinders. The model results showed an excellent agreement with experimental values. Youssef et al. [10] developed a stress–strain model for concrete confined by fiber reinforced polymer (FRP) composites. The model was based on the results of a comprehensive experimental program including large-scale circular, square and rectangular short columns confined by carbon/epoxy and E-glass/epoxy jackets providing a wide range of confinement ratios. Ultimate stress, rupture strain, jacket parameters, and cross-sectional geometry were found to be significant factors affecting the stress–strain behavior of FRP-confined concrete. Such parameters were analyzed statistically based on the experimental data, and equations to theoretically predict these parameters were presented. Experimental results from this study were compared with the proposed semi-empirical model as well as others from the literature. However, most experimental studies to date on the confinement of concrete columns with FRP have been conducted without considering the possible scale factors involved. The behavior of small specimens may be affected by the restraining influence of the end-bearing plates, which can lead to local non-homogeneities that will cause higher standard deviations and produce results that are not representative of larger specimens [11,12]. Most codes provide weighting factors for concrete strengths measured from cylinders having a diameter different than the standard value of 150 mm. Nevertheless, in spite of all these inconveniences, small specimens are widely used since they are more economical, requiring less material, smaller molds, less expensive testing equipment, and limited space for storage. They are also easier to handle, therefore saving time and reducing the risk of damage during handling. Sener et al. [13] studied the size effect on axially loaded reinforced concrete. The test specimens were geometrically similar pin-ended concrete columns of different sizes (in the ratio 1:2:4) giving slenderness ratios of 9.7, 18.0, and 34.7. The columns had square cross sections of sides 50, 100, and 200 mm, and varied in length from 0.14 m to 2.08 m. It was observed that for all slenderness ratios considered in the investigation, the failure loads exhibited a size effect in which the nominal stress at maximum load (failure load divided by cross-sectional area) decreased as the size was increased. This contradicts the