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Size effect in circular concrete-filled steel tubes with different diameter-to-thickness ratios under axial compression

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Axial compression tests of circular concrete-filled steel tubes with different diameters (219 mm, 426 mm, and 630 mm) and ratios of tube diameter to steel thickness (55 and 88) were conducted to investigate the effect of size on the bearing capacity. The experimental results indicated that the peak nominal stress decreased as the size increased, and the decrease in the nominal stress due to the size effect increased at higher ratios of diameter to thickness. At the peak load moment, an increased specimen diameter corresponded to a decreased hoop stress in the steel tube as well as a decreased concrete strength due to the confinement effect of the steel tube. When the ratio of diameter to thickness increased, the extent of reduction of the hoop stress and the confining effect of the steel tube influenced by the increasing specimen size increased. However, the vertical stress in the steel tube was increased at increased size, and increases in the ratio of diameter to thickness improved the increase degree of the vertical stress of steel tube due to the enlargement of specimen size. Hence, the vertical bearing capacity of the steel tube was affected by both the specimen size and the ratio of diameter to thickness. Based on the size effect law (SEL) proposed by Bazant, and taken the effect of the ratio of diameter to thickness into consideration, a size-dependent formula to evaluate hoop stress in the steel tube was developed. A size-related model considering situations with different ratios of diameter to thickness was established in order to estimate the bearing capacity of large-size circular concrete-filled steel tubes. The model and experimental results showed good agreement.

1. Introduction

Concrete-filled steel tubes (CFTs) possess the superior mechanical properties of high bearing capacity, good plasticity, and toughness, with the advantage of convenient construction suitable for modern engineering technology. CFTs also satisfy the structural requirements for high-rise buildings, large-spans bridges, heavy-load structures, and construction in harsh environments. Thus, CFTs are widely used in high-rise and super-high-rise buildings, industrial plants, long-span bridges, and underground structures, providing good economic benefits and construction effects. As the required bearing capacity increases, the component sizes for CFT structures also increase. For example, the diameters of the CFT columns used in the outer frame of the Jin Tower in Tianjin, China, is 1200–1600 mm, and the maximum diameter of the CFT columns used in the bottom layer of the Union Square building complex in Seattle, WA, USA, is 3050 mm. The safety of these large-size structures, particularly concerning the effect of specimen diameter on the confinement effect of the steel tube, has become a very concerning issue. So far, studies on the bearing capacity of CFTs have used specimens with diameters below 450 mm, with many focusing on the range of 100–200 mm [1], without showing the existence of a size effect in CFTs. However, the existence of size effects is increasingly accepted in theory [2–7] and has been confirmed by many experiments on plain concrete samples and concrete components, such as reinforced concrete (RC) beams, RC columns, RC beam-column joints, and concrete confined by fibre-reinforced plastic (FRP) [8–15].

The size effect on the bearing capacity of concrete columns has been studied from two perspectives, analysing the effect of material size on the behaviour of plain concrete under axial compression and the effect of component size on the confinement effect of enclosing reinforcements.

With increases in specimen size, concrete develops many more internal defects, increased heterogeneity, and quasi-brittleness; the size effect clearly exists in plain concrete. The study of statistical size effect considers the random distribution of internal defects of concrete; therefore, the corresponding study describes size

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effect based on statistical theory (1951). A deterministic size effect is observed in the uniaxial compression of short concrete specimens with non-symmetric stress fields (wall friction), attributed to a global energy release during the buckling of inclined or transverse bands of microslabs in axial splitting failure [19]. The effect of size on the uniaxial compression of concrete has been extensively investigated. Gonnerman [16] found and verified experimentally the size effect on the strength of concrete. Axial compression tests on concrete cylinders with diameters of 152–914 mm, conducted by Blanks et al. [17], showed that increases in diameter decreased the compressive strength of the cylinders, with decreases in strength reaching 16%. Weibull [2] believed that the various defects causing strength reduction in concrete were randomly distributed and therefore proposed a statistical theory for the size-effect distribution law. Sabnis et al. [18] considered that the effect of size on concrete strength was influenced by many factors, and performed a regression analysis on compressive concrete strengths as measured by 12 researchers. They proposed a formula for calculating the compressive strength of concrete as a function of size, considering the influences of concrete strength, age, and curing conditions. Bazant et al. [19] demonstrated that energy dissipation after peak loading was related to specimen size because of the localization of strain softening damage, and thereby proposed a size-dependent model of the compressive strength of concrete based on fracture mechanics. Kim et al. [20] applied Bazant's size effect law (SEL) for tensile strength [21] to the compressive strength of concrete and then derived a size-effect formula for the compressive strength of concrete cylinders, called the modified size effect law (MSEL) of Bazant, based on a statistical analysis of 678 experimental data including 20 specimens from Smadi et al. [22], 172 from Gonnerman [16], 26 from Blanks et al. [17], 337 from Kesler [23], and 123 from Murdock et al. [24]. Noguchi et al. [25] experimentally studied the effect of size on the cylinder compressive strength of high-strength concrete and provided two formulas for calculating the compressive strength of concrete cylinders, considering the size effect based on the statistical theory of Weibull [2] and the model of Kim et al. [26], respectively. Sakino et al. [27] determined the size effect reduction factor for the compressive strength of concrete cylinders by a regression analysis of 26 test data from Blanks et al. [17]. Yi et al. [28] experimentally investigated the compressive strengths of concrete samples with different sizes, shapes, and pouring directions, obtaining new parameters for the MSEL formula by fitting the test results. The existing results indicate that the uniaxial compressive strength of concrete is decreased as the specimen size increases; the decrease can be estimated by different theoretical methods.

Because of the interaction between concrete and confining materials such as steel and FRP, the size effect in confined concrete is more complicated than that in plain concrete materials. For concrete confined by circular spiral lateral steel subjected to axial compression, Kim et al. [20] analysed the existing test data and concluded that decreasing the volumetric ratio of lateral steel increased the effect of size on the compressive strength of the confined concrete, and then proposed a formula for estimating the compressive strength of confined concrete that considered the interaction between the specimen size and the volumetric ratio of lateral steel, based on the MSEL model. After conducting an axial compression experiment on concrete specimens confined by circular and square lateral steel with the maximum specimen size of 800 mm, Li et al. [29,30] found that the peak stress of the confined concrete decreased as the size increased, and degree of decrease was enlarged as the volumetric ratio of lateral steel lessened. A size-dependent stress–strain constitutive model of confined concrete under varied volumetric ratios of lateral steel was established based on the SEL model [21]. An experimental study on concrete confined by carbon FRP (CFRP), conducted by Akogbe et al. [31], showed that the compressive stress of the confined concrete decreased when the diameter was increased from 100 mm to 300 mm. Through axial compression tests on concrete confined by aramid FRP (AFRP) of different sizes, Wang et al. [15] concluded that increases in size caused decreases in the strength of AFRP-confined concrete at the peak bearing capacity of the specimen; the degree of decrease was increased as the confinement ratio of AFRP decreased. A formula to estimate the strength of AFRP-confined concrete considering the influence of both size and confinement ratio was established based on the SEL [21]. Elkadi et al. [32] tested concrete cylinders under triaxial compression and found that the triaxial compressive strength of concrete was decreased for increased specimen size, and then fitted the size effect formula for estimating the triaxial compressive strength based on the SEL [19]. Previous research has shown that the peak stress of confined concrete under axial compression is decreased with increasing size, and degree of decrease is increased with decreases in the confinement factor (such as the volumetric ratio of lateral steel or the confining ratio of FRP). Formulas for the peak stresses of various types of confined concrete under axial compression relating to the interaction of specimen size and confinement factor have been obtained based on the basic SEL [19,21].

For the specific confined concrete type of CFT under axial compression, research on the size effect is limited. Luksha et al. [33] performed axial compression tests on 10 short CFT columns with diameters ranging from 159 mm to 1020 mm, all with different concrete strengths and ratios of diameter to thickness (D/t). The results showed that increased column sizes corresponded to changes in the failure mode of the columns from plastic to shear. Experimental studies conducted by Yamamoto et al. [34] and Chen et al. [35] found that the peak stress of circular CFT subjected to axial compression was insensitive to specimen size increases for D/t values of less than 50. Based on the analysis of a micro-plane numerical model of CFTs with different D/t subjected to axial compression, Caner et al. [36] speculated that the steel ratio of CFTs which are affected by size ranges from 4% to 8%, or D/t of 50 to 100. Wang et al. [37] tested short cylindrical CFT columns with the constant D/t of 88 and diameters ranging from 219 to 820 mm under axial compression. The nominal stress of the specimen was decreased with increases in the specimen size, while the tested hoop stress of the steel tube was decreased as the size increased; therefore, the confinement effect on concrete provided by the steel tube was subject to size effects. A size-related model was proposed to predict the bearing capacity of CFTs. Existing research has implied that, for large values of D/t, the peak stresses of cylindrical CFTs subjected to axial compression experienced size effects; however, when D/t is varied, the influence of interaction between size and D/t remains unclear.

Actually, the columns used in the practice engineering are always subjected to eccentric compression but not to uniaxial compression. While the axial compression performance is the basic performance of the column, the calculation of axial bearing capacity is also the basic index of engineering design. The research on the size effect of the compressive performance of the concrete-filled steel tube (CFT) column is also helpful for the mechanism analysis of the size effect on its performance under eccentric compression, bending moment or even seismic action. Currently, the studies of the size effect on the mechanical properties of CFT columns are lack of strong scientific basis. Therefore, this paper started to investigate the size effect on CFT columns from the basic performance, namely axial compression performance. In this study, the axial bearing capacities of cylindrical CFTs with different diameters and D/t values were investigated experimentally. The diameters of the specimens were 219, 426, and 630 mm; the D/t values were 55 and 88. Under different D/t values, the size effects on