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Mechanical behavior and size effect of moderate high-strength RC columns under monotonic and cyclic axial compression

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A B S T R A C T

The reliable design of reinforced concrete (RC) structures against external mechanical forces, including earthquake-induced, impact and other types of forces, necessitates a clear understanding of the mechanical behavior and size effect of moderate high-strength RC structural members under cyclic loading. This study presents the results of an experimental study on a series of geometrically similar moderate high-strength RC columns under monotonic and cyclic axial compression. A total of 16 moderate high-strength RC columns with different structural dimensions (in the ratio 1:2:3:4) were tested. The cross-sectional size of the columns was between 200 mm and 800 mm, and the length varied from 600 mm to 2400 mm. The overall mechanical performances of the moderate high-strength RC columns, including the failure patterns, the hysteretic curves, the nominal compressive stress-strain relationships, the peak load-carrying capacity, the energy-dissipation capacity, the nominal compressive strength, the concrete softening behavior and the buckling/necking of steel rebar were observed and explored. The test observations indicate the existence of size effect in relatively larger-sized moderate high-strength RC columns under both monotonic and cyclic axial compression, and the RC columns under cyclic loading pronounce a more obvious size effect. It is found that the bi-logarithmic plots of nominal compressive strengths for different moderate high-strength RC columns follows closely the "size effect law (SEL)" proposed by Bažant.

1. Introduction

As the dimensions of engineering structures, such as high-rise buildings, cross-sea bridges and underground tunnels, are becoming larger and larger, the use of high-strength reinforced concrete (RC) structural members is getting more and more popular in present constructions. The reliable design of RC structures against external mechanical forces, including earthquake-induced, impact and other types of forces, necessitates a clear understanding of the mechanical behavior of high-strength RC structural members under monotonic and cyclic loading. Moreover, just as demonstrated in lots of experimental observations [1–5], the nominal strengths of RC structural members, involving columns, beams, and beam-column connections, present a pronounced size effect due to the heterogeneity of concrete and the complex mutual effect between steel rebar and the surrounding concrete. Thus, it necessitates the development of accurate and reliable theories for their analysis and assessment. Of particular importance is the understanding of the mechanical properties and size effect of high-strength RC columns under cyclic axial compression for the seismic retrofit and design of these members.

1.1. Size effect on RC members

The global mechanical properties and the failure mechanism are of fundamental importance to the analysis of RC structures. RC structures consist of two separate materials with very different characteristics, namely, steel and concrete. Concrete is a very complex composite material including aggregate, cement mortar, micro-cracks, voids and all kinds of mixtures. Concrete has been demonstrated as a quasi-brittle material, and it presents obvious size effect, such that the nominal stress σ_{Nu} at failure decreases as the characteristic dimension D of the structure increases. The efforts in [6] have also indicated that there is a size effect on steel rebar, related to the extent of the rebar's martensitic zone. In addition, size effect can be found in different RC structural members for different types of loading, because the size effect should be caused by the release of energy stored in the structure that can vary according to the structural size and type of a failure [7]. Numerous theoretical, experimental and numerical efforts [8–27] have been

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conducted to discover and confirm the size effect behavior in plain concrete and RC structural members. Generally, the available experimental observations prove the existence of size effect in RC structures. Simply to say, the size effect in RC structural members should be caused by (1) the size effect in the materials (i.e. concrete and steel), and (2) the mutual effect between the reinforcing bars and surrounding concretes.

Based on different principles, different size effect models could provide good correlations between the theoretical values and the test data in the range of the majority of existing experiments, as can be seen in the schematic diagram Fig. 1. However, although a great deal of experimental tests on size effect have been conducted, the RC structural sizes are still limited to a relatively small range. It remains unknown for the size effect of larger-sized RC structural members, as can be concluded from Fig. 1 that different size effect models predict different trends for larger-sized RC structures. Therefore, much more theoretical, experimental and numerical efforts for larger-sized RC structural members are still required.

1.2. Influences of concrete strength grade and loading pattern on size effect

The mechanical behavior and size effect of RC structural members under monotonic and cyclic loading have been studied extensively over the past few decades [1–5,12,16,17,23,28,29]. The efforts have proved the existence of size effect in RC structures under different loading patterns. Accordingly, the fatigue failure occurs when a concrete structure fails catastrophically at less than the design load after being exposed to a large number of stress cycles. It is a process of progressive and permanent internal damage in a material subjected to repeated loading [30]. The increase of the use of high-strength concrete and the increase of the structural size would make this issue more vital. Many efforts have been conducted so far to investigate the mechanical behavior of RC structural members under cyclic loading [5,12,16,17,23,28,29]. However, the majority of the existing studies concentrated on normal-strength concrete structures rather than (moderate) high-strength concrete structures. The (moderate) high-strength concretes are known to exhibit obvious brittle behavior, which may introduce obvious size effect in the RC structural members. Bažant and Schell [10] investigated the fatigue fracture of geometrically similar high-strength three-point bend notched concrete beams having different sizes subjected to cyclic loading. Ho and Pam [14] studied the inelastic design of low-axially and reversed cyclic laterally loaded high-strength RC columns based on experimental efforts. However, the cross-sectional size mentioned above was limited to 325 mm × 325 mm.

In reality, numerous RC structural members are working under repeated cyclic loading, such as the RC crane beams under the mobile crane, the RC bridges subjected to the vibration produced by the traffic and the port/coastal engineering structures impacted by the waves. However, the loading patterns of the existing experimental efforts on RC columns are mainly monotonic axial compression [2], monotonic eccentric compression [1,3] and laterally reversed cyclic loading [12,14,16,17,23,28,29]. Only a few studies have been concerned with axially repeated cyclic loading. Abbasnia and Ziaadiny [31] investigated the behavior of concrete prisms confined with FRP composites under axial cyclic compression. Wang et al. [32] tested a group of CFRP-confined large circular RC columns subjected to repeated cyclic axial compression. Ozbakkaloglu and Akin [33] studied the behavior of FRP-confined normal- and high-strength concrete under repeated cyclic axial compression. Nevertheless, all of these studies are mainly concentrated to FRP- or CFRP-confined RC columns rather than steel-confined RC columns, and their size range was limited to 150–300 mm.

1.3. Objectives of this work

In the previous work of [34], the size effect of normal-strength (circa 30 MPa) and moderate high-strength (circa 60 MPa) RC columns with the maximum structural size (cross-sectional width) of 800 mm subjected to monotonic axial centric compressive loading was experimentally studied. The test observations demonstrate the existence of size effect in larger-sized RC columns.

This study presents the results of an experimental study, aiming at filling the existing research gaps outlined above and extending our previous work of [34]. The main objectives of this study are, on one hand to study the global mechanical behavior and size effect of relatively larger-sized moderate high-strength RC columns subjected to repeated cyclic axial compressive loading, and on the other hand to discover the effect of loading patterns on the size effect. A total of 16 moderate high-strength RC columns

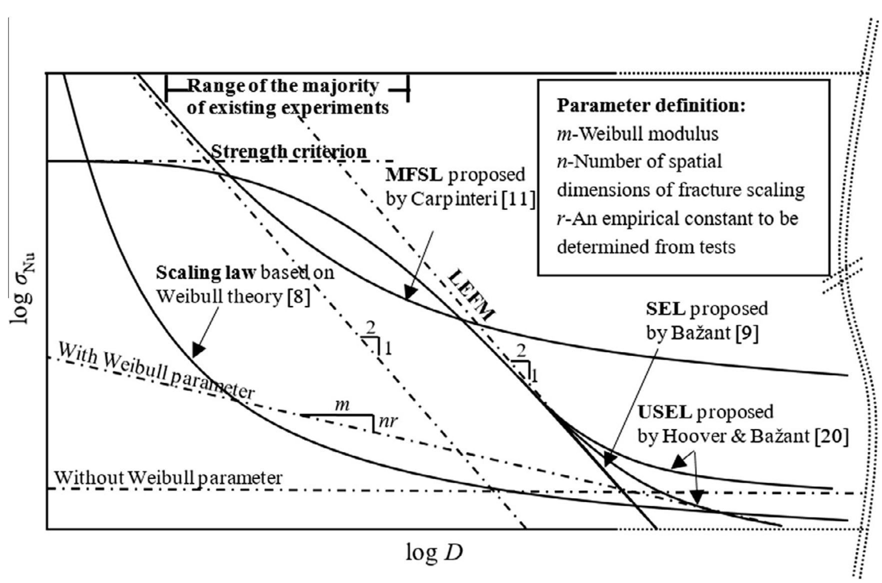

Fig. 1. Dependence of nominal strength σ_{Nu} on structural size D based on different principles.