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Effect of cross-section size on the flexural failure behavior of RC cantilever beams under low cyclic and monotonic lateral loadings

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ABSTRACT

The objectives of this study are, on one hand, to present an experimental campaign on the flexural failure behavior of RC beams under both low cyclic and monotonic lateral loadings, and on the other hand, to discover the effect of cross-section size on the global mechanical properties of RC beams. Five groups of geometrically similar RC cantilever beams, with cross-section sizes range from 200 mm to 1000 mm and a shear-span ratio of 4 (length to shear span) were experimentally tested. Moreover, a 3D meso-scale numerical method, which could consider both the heterogeneity of concrete material and the nonlinear interaction between reinforcing bars and surrounding concretes, for the simulation of failure of RC members was developed, and some numerical tests were established based on the experimental campaign. The tested results demonstrate the presence of size effect in flexural failure of RC beams under both low cyclic and monotonic lateral loadings. Specifically, the effects of structural size on the seismic performances of the RC beams, involving the failure pattern, the ductility, the stiffness degradation and the load carrying capacity, were extensively investigated based on the combined experimental and numerical tests. Under cyclic loading, due to the low cyclic fatigue damage behavior and for the fact that failure always takes place in concrete which is a quasi-brittle engineering material, all the tested beams could exhibit a more quasi-brittle failure pattern, and consequently the flexural failure of the beams presents a stronger size effect compared with that under monotonic loading.

1. Introduction

The size effect is understood as any dependence of nominal strength and brittleness on structural size. Generally, the nominal strength decreases with increasing structural size, while the brittleness increases with increasing structural size. Theoretically, based on the fracture mechanics, several researchers have demonstrated that, concrete becomes ductile on a small scale and it becomes brittle on a large scale [1], and numerous test observations [3–5] have proved that, the size effect behavior of concrete is mainly due to its inherent quasi-brittle feature which is originally caused by the inhomogeneity of the material. From a mesoscopic point of view, concrete is full of micro-cracks, and these micro-cracks become active and begin to propagate upon loading. A strong stress concentration would develop around the crack tip and the micro-cracks propagate to major macro-cracks that lead to the eventual failure of the structure. Two size effects are of a major importance: deterministic size effect and statistical size effect [2]. A deterministic (or energetic) size effect is caused by the formation of a region of intense strain localization with a certain volume (also called ***f**racture **p**rocess **z**one*, FPZ) which always precedes discrete macro-cracks. In turn, a statistical size effect is caused by spatial variability/randomness of the local material strength. A combination of the deterministic size effect law with the statistical size effect law led to a general energetic-statistical theory. The deterministic size effect occurs for not too large structures and the statistical size effect is obtained as the asymptotic limit for very large structures. The deterministic size effect can also occur in RC members wherein the failure always takes place in concrete which is a quasi-brittle engineering material. For reinforced concrete (RC) structures, the interaction between concrete and reinforcement has a significant influence on the development of cracks in concrete. Therefore, the size effect in RC members is rather a structural mechanics problem, which includes not only the material size effect in concrete, but also the size effect contributed by the nonlinear interaction between concrete and rebar, than a material science problem [6]. Generally, for the fact that failure always takes place in concrete which is a quasi-brittle engineering material, many experimental results on RC columns [6–8], RC beams [9–12] and RC beam-to-column connections [13] have demonstrated the existence of size effect in RC elements. The present research works mainly concern geometrically similar RC beams that are designed to fail in flexure.

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1.1. Available test efforts on flexural failure of RC beams

The shear failure, the flexural failure and the flexural-shear failure are three main failure patterns for RC beams under loads. Generally, the shear behavior of concrete components exhibits a brittle failure mode, and then a size effect may be expected for the fact that the size effect always occurs in RC elements if failure takes place in concrete that is a quasi-brittle engineering material [14]. In our previous work of Jin et al. [12], five groups of geometrically similar RC beams, with cross-section sizes range from 200 mm to 1000 mm and a shear-span ratio of 2 (length to depth), were tested under cyclic lateral loading. The test results have demonstrated the existence of size effect in shear strength of RC beams.

For the flexural failure in RC beams, many test efforts have been conducted to explore the possibility of existence of size effect. For instance, in the work of Weiss et al. [15], sixteen groups of RC beams having different concrete strengths and percentages of longitudinal steel bars were tested. They found that, the nominal moment-carrying capacity of all beams was relatively constant, while the overall ductility was dependent on the constant-moment zone length with larger specimens demonstrating a more brittle response. The test results presented by Alca et al. [16] also indicated that there was no obvious size effect in the flexural compressive strength of RC beams. However, some other test efforts [17–23] have shown the presence of size effect in flexural strength. For instance, in the experiment of Rao et al. [19], three groups of RC beams with cross-sectional depths of 100 mm, 200 mm and 400 mm were tested, which were designed with varying percentages of flexural reinforcement, i.e. 0.15%, 0.30%, 0.60% and 1.0%. The RC beams were tested under four-point loading to study the flexural behavior under uniform bending moment. Their test results indicated that the flexural strength of RC beams decreased as the depth increases. Bosco et al. [20] also performed tests on RC beams with various beam depths and longitudinal steel percentages. The test results indicated that, the brittleness of the structural member increases by increasing the structural size and decreasing the longitudinal steel percentages. Yi et al. [21] tested a series of RC beams with same percentages of flexural reinforcement subjected to four-point loading. The test observations illustrated that, the flexural compressive strength at failure exhibited an obvious size effect, and the corresponding peak strain and the ultimate strain decrease as the structural size increases. Furthermore, Kim et al. [22] and Yi et al. [23] also demonstrated the presence of size effect in flexural compressive strength of RC beams.

The contradictories in the test results for the investigation of size effect in flexural failure of RC beams indicate that, the presence of size effect may strongly depend on how the failure takes place. In general, for over-reinforced or less-reinforced beams, the failure is mainly due to the fracture of concrete, which exhibits brittleness and leads to an obvious size effect. While for appropriate reinforced beams, the failure is usually less brittle or ductile, and the nominal strength would show no obvious size effect.

1.2. Effect of seismic loading on the failure behavior of RC beams

Under seismic loading, the development of cracks in RC beams changes, the bonding between concrete and rebar could be deteriorated under low cyclic fatigue loading, and the failure always takes place in concrete which is a quasi-brittle engineering material, consequently the beam becomes more brittle as compared to that under monotonic loading. Fatigue failure happens as a concrete structure fails at less than the design load after exposure to a large number of stress cycles, causing the degradation of stiffness and strength. It is a process of progressive and permanent internal damage in a material subjected to repeated loading. Lots of studies have been conducted to study the failure behavior of RC beams under repeated or cyclic loadings, e.g. in the work of Moretti and Tassios [24], Mahal et al. [25] and Dadi and Agarwal [26]. However, less work has been focused on size effect. Recently, Barbhuiya and Choudhury's [13] test efforts on RC beam-column connections have indicated that, under cyclic loading, the three categories of beam-column connections (i.e. beam weak in flexure, beam weak in shear and column weak in shear) exhibit an obvious size effect. In our previous efforts [12,27], the test observations have also indicated that, under low-cyclic fatigue loadings, even for balanced-reinforced RC specimens, because of that the failure always takes place in concrete which is a quasi-brittle engineering material, the failure of the RC beams or columns is still brittle, and the nominal shear strength exhibits a pronounced size effect.

1.3. Scope of the present research work

The objectives of the present study are, on one hand, to present an experimental campaign on the flexural failure behavior of RC beams under both low cyclic and monotonic lateral loadings, and on the other hand, to discover the effect of cross-section size on the global seismic performances of RC beams. With respect to the previous work [12] in which the size effect of shear failure of RC beams was experimentally explored, the innovative points of the present study are to examine the size effect of flexural failure of RC beams by experimental and numerical approaches.

Five groups of geometrically similar RC cantilever beams with cross-section heights ranging from 200 mm to 1000 mm and a shear-span ratio of 4 (depth to shear span) were experimentally tested. Moreover, a 3D meso-scale numerical method, which could consider both the heterogeneity of concrete and the nonlinear interaction between reinforcing bars and surrounding concretes, for the simulation of failure of RC members was developed, and some numerical tests were conducted based on the experimental campaign. Finally, the 3D meso-scale simulation method was extended to examine the size effect in larger-sized RC beams with a maximum cross-sectional height of 2000 mm.

2. Test results

2.1. Specimen description and materials properties

Five groups of geometrically similar RC cantilever beams with different structural sizes, subjected to monotonic and cyclic loading were tested. The dimensions, shape, loading point locations, specimen label, and reinforcement details of specimens used in the experiment are shown in Fig. 1 and Table 1. The cross-sectional depth of the beams tested ranged from 200 mm to 1000 mm. The tested RC beams presented in Fig. 1 were designed to fail as flexural failure, and a shear-span ratio (length to depth) of 4 was utilized. There were three specimens designed for every group of tested specimens having the same structural sizes, in which one of them was subjected to monotonic loading, and the other two were designed to bear cyclic loading. The specimens under monotonic loading were named as MB, and the other two specimens under cyclic loading were named as CB. Herein, the letter "M" means the "**M**onotonic loading", "C" means the "**C**yclic loading", and "B" denotes "**B**eam". A total of 15 RC beams were thus tested.

The mixture proportions of the concrete utilized in the present tests are given in Table 2. 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). The compressive and tensile strengths of concrete, which are measured by uniaxial compressive and splitting tensile tests based on the currently utilized standard codes of China, are also presented in Table 2. Moreover, the detailed information about the parameters of the reinforcing steel bars are listed in Table 3, including the diameters, the yield strength and the ultimate strength, etc. In the tests, the strength of concrete, reinforcement ratio, stirrup ratio, and shear span ratio were kept the same for all RC beams.

It is to be noted that, the aggregate sizes were not scaled to the