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Effects of predamage on the compression performance of CFRP-confined rectangular steel reinforced concrete columns

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the axial compressive behavior of predamaged steel reinforced concrete (SRC) rectangular short columns confined by carbon fiber reinforced polymer (CFRP) laminates. The authors tested 13 large-scale CFRP confined SRC columns. The primary variables were the predamage level and number of CFRP's layers. All confined columns failed in the mode of CFRP laminates rupture after peak load. Both the working strain of CFRP and the peak load of columns decreased with predamage level. This paper also presents a new finite element numerical model for the nonlinear analysis of confined columns. This model was verified against experimental results, which led to the adoption of concrete damaged plasticity model (CDP). Simulation confirmed that the confinement effects of concrete provided by CFRP laminates is mainly restricted in the corner zones and the core area surrounded by the steel in column sections. Both the circumferential CFRP strains and confined concrete compressive stress significantly decreased with the increasing predamage level under peak load states.

1. Introduction

Fiber reinforced polymers (FRP) have superior properties including light weight, high strength and easy application. These properties make its application highly recommended for structure rehabilitation to concrete [2] and steel [20]. FRP jackets are used to provide continuous confinement to reinforced concrete columns, which improve both capacity and the ductility [4].

A lot of research has been done to investigate the performance of FRP-confined concrete columns. Mirmiran et al. [12] concluded that many parameters, such as concrete strength, fiber volume, corner radius and aspect ratio of column sections, determine the confinement effectiveness of concrete columns. Park et al. [13] found experimentally that the compressive capabilities of concrete cylinders with two-layers of CFRP were less than twice as effective as concrete cylinders with one-layer of CFRP. Vasumathi et al. [14] concluded that the RC column confined by CFRP laminates with 30 mm spacing provided an economical advantage compared to that of 20 mm spacing. Additionally, Yousef [18] found that rounding the edges of a square cross-section played a significant role in delaying the rupture of FRP, and the confinement efficiency was also directly influenced by corner radius. Furthermore, [5] investigated the stress-strain behavior of CFRP wrapped square concrete specimens and recommended a radius of at least 25 mm [15]. performed a series of experiments and found that if the ratio of depth to width on the cross-section increased from 1.0 to 2.0, the strength gained in confined concrete columns decreased, until it became insignificant when the ratio exceeded 2.0. Some similar conclusions were also given in finite element methods on rectangular concrete columns by [10].

For most structures, the pre-existing loads cannot be totally eliminated before strengthening construction; the in-service components usually work with damage and cracks. So, it is more valuable to research the mechanical properties of predamaged concrete with confinement. Liu et al. [9] and Ma et al. [11] gave axial compression tests on concrete columns, which were assigned three different damage levels before FRP wrapping. Their results showed that different predamage levels had little effect on the ultimate strength of confined columns. According to Ghernouti et al. [7], the square concrete columns were damaged up to 70% of their ultimate strength in compression before strengthening. At the same time, initial intense cracks appeared parallel to the loading axis. Compared with the unstrengthened reference column, the strengthened specimens appeared to have decreased initial axial compressive stiffness, but the ultimate strength and ultimate strain increased. Guo et al. [8] further found the effect of the pre-existing damage effect on the ultimate strength, and the axial strain of the CFRP-confined concrete was more significant for normal strength concrete columns than high strength columns. Wu et al. [16] tested many concrete cylinders involving varying degrees of damage, concrete

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grade, and confinement pressure; they then gave the quantified predamage effect in terms of a damage index, which included compressive strength, strain capacity, and initial elastic modulus.

However, very limited data are available on the effect of predamage on the axial compressive performance of CFRP-confined large-scale steel reinforced concrete (SRC) columns. In this paper, 13 steel reinforced concrete rectangular short columns were designed and tested to investigate the effect of predamage level and the number of CFRP layers on the columns' axial compressive behavior. Based on experimental results, a suitable finite element model was developed, and the confinement mechanism was analyzed in-depth.

2. Experimental programs

2.1. Test specimens

Thirteen SRC column specimens were designed with a height of 800 mm and a rectangular cross section of 250 mm × 300 mm. Each corner of confined columns section was chamfered with a curve of 20 mm radius before strengthening to avoid the premature failure of CFRP. All columns were reinforced longitudinally using four rebars with a diameter of 16 mm and transversely using stirrups with diameter of 6 mm. The I-shaped steel was placed in the center of the cross section, which were 100 mm high and 68 mm wide. The thickness of web and flange were 7.6 mm and 4.5 mm, respectively. Strengthened columns were partially wrapped with 100 mm CFRP laminated strips, also having the spacing of 100 mm. Fig. 1 shows the dimensions and reinforcement details.

The mechanical properties of concrete, reinforcement bars and I-steel were tested and listed in Table 1. All specimens were cast using one batch of concrete. The average value for the compressive strength of three 150 × 150 × 150 mm cubes was 32.1 MPa. These cubes were cast along with the specimens, at the age of 28 days.

The average yield strength of the longitudinal bars and transverse bars was 465.0 MPa and 210.0 MPa, respectively. The I-steel's yield strength was 227.0 MPa. All the steel-related mechanical data were obtained from tensile coupon tests.

Additionally, the mechanical properties of CFRP laminate and epoxy resin listed in Table 1 were provided by manufactures. Moreover, the nominal thickness of CFRP laminate was 0.111 mm, and the normal tensile bond strength of the interface between concrete surface and CFRP was 3.9 MPa.

The variables among the specimens include the CFRP layers n and the axial predamage levels m (the ratio of the axial preloading to the actual axial compressive capacity of non-predamaged SRC 0–0 column). All the specimens were named as SRC n–m, as shown in Table 2, it can be found that the specimens were divided into three groups with respect to different CFRP layers n (varying from 0 to 3) and the predamage level, m, varied from 0.50 to 0.75.

2.2. Test procedures

When strengthening existing columns, loading conditions had to be considered. When columns were subjected to a constant maintained load, the reinforcement and concrete had a stable working strain which allowed the FRP to work with the lagging strain. If the columns were unloaded before strengthening, the predamaged concrete only sustained the residual plastic strain. Cao et al. [3] designed a self-balanced loading device and tested small strengthened concrete columns in uniaxial compression with different maintained loading. In their device, a jack was used to preload the columns to a certain level; then a nut was tightened to keep the load secure; a pressure sensor was installed to measure the load. When studying the effect of predamage on the stress-strain relationship of confined concrete under monotonic loading, some scholars [9] and [16] unloaded the concrete specimens at the specific loadings on the post-peak zone of the load-deformation curve, which could achieve stable residual strain of concrete and realize the definite damage levels, but these did not conform to the actual application. Meanwhile, Wang et al. [17] unloaded CFRP-confined reinforced concrete rectangular columns under the service load condition. In this case, two preload levels were set as 40% and 80% of the control column's peak load. These columns went through five preloading and unloading tests. After that, the residual plastic concrete strain became stable; then, the columns were strengthened by FRP, and tested under uniaxial compression in the end. As for the full-scale short column in this paper, due to the large bearing capacity of the composite columns, it is difficult to realize a self-balanced device which can maintain a load level in the laboratory. Thus, the preload pattern proposed by Wang et al. [17] was chosen.

As shown in Fig. 2, a hydraulic compression testing machine with a maximum capacity of 5000 kN was used. The spherical hinges and steel bearing plates guaranteed the concentric compressive load. The test procedure can be summarized as three steps: preloading, strengthening and formal loading.

In the preloading program, referring to the method by Wang et al. [17], each specimen was axially loaded with five cycles of loading and unloading at a rate of 2 kN/s, and the preload pattern is shown in Fig. 3. However, it was difficult to achieve the effect of plasticity damage in a concrete column at a low preload level; thus, the parameter of the predamage level began from 0.5, which led to a stable residual concrete strain followed by pre-crack formations in the columns. After the preloading program was finished, CFRP laminates were applied to these columns.

In the formal loading process, the specimen was subject to a monotonic static axial load at a rate of 1 kN/s in steps, where the load was kept constant for three minutes to record cracks propagation in each steps. Initially, each load step was 150 kN; then, it turned to 100 kN after the first concrete crack appeared. Finally, when the longitudinal rebar yielded, the column became unstable, so that loading was controlled by the axial displacement from LVDTs in Fig. 2 until the column failed.

Strain gauges were installed on the longitudinal reinforcement bars and on the I-steel at middle column height for each column before casting the concrete. After the epoxy resin cured, strain gauges were installed along the hoop direction on CFRP laminates at different positions numbered T1 to T6, as shown in Fig. 1. A calibrated load sensor was placed under the steel plate below the column to measure the effective load. Two LVDTs were also arranged at the bottom of the loading plate to measure the longitudinal deformations of each column, as shown in Fig. 2a.

3. Experimental results and discussion

3.1. Failure process

3.1.1. Non-predamaged columns

The authors designed three control specimens including SRC 0-0, SRC 2-0 and SRC 3-0. SRC 0-0 column was a typical steel reinforced concrete column without strengthening, while the other two were strengthened with two or three layers of CFRP. However, all three had no preloading process.

For the unconfined SRC 0-0 column, the concrete first cracked at column top (692.0 kN). After that, the I-steel and reinforcement bars yielded one after another (1090.0 kN and 1150.0 kN), along with concrete cover peeling off until it got to the peak load (1172.0 kN). When reaching the ultimate state (816.0 kN), the longitudinal reinforcement bars extruded outward and the core concrete was crushed out.

Fig. 4 shows the failure process of the SRC 2-0 column. The first-cracking identified by the arrow in Fig. 4b was produced by a higher load (1045.0 kN) than SRC 0–0. Then, some small concrete cracks propagated, and the CFRP strain increased. When the applied loads reached 1470.0 kN, the I-steel yielded, and the CFRP strain also