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Field testing of RC slabs with openings strengthened with CFRP

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ABSTRACT: Introducing openings in existing reinforced concrete (RC) slabs can severely weaken the slabs due to the cut out of both concrete and reinforcing steel. There are several traditional approaches to strengthen RC slabs with openings; however these approaches can be cumbersome, expensive, and may require significant usable floor area. This paper reports field tests on the use of Carbon Fiber Reinforced Polymers (CFRP) strengthening alternatives to restore the flexural capacity of the RC slab after having large openings cut out in the positive moment region. The uniqueness of this study is that the tests were performed on an existing multi-storey RC structure that was scheduled for demolition. Testing a real structure allowed incorporating factors and boundary conditions that typically cannot be simulated in the laboratory. Five tests on five different slabs were conducted to evaluate the ability of the CFRP strengthening alternatives to restore the flexural capacity of the slab after introducing the openings. Three different strengthening techniques were investigated to determine the most effective system for strengthening. The three different strengthening techniques are the use of externally bonded (EB) CFRP laminates, EB CFRP laminates with CFRP anchors, and Near Surface Mounted (NSM) CFRP strips. Test results showed that the three strengthening techniques enhanced the load-carrying capacities of the slabs with openings with the NSM technique more effective than the EB technique. Use of CFRP anchors with EB laminates prevented complete detachment, and hence enabled the slab to restore its full flexural capacity.

1 INTRODUCTION

In existing Reinforced Concrete (RC) structures it is very often required to create openings in the slabs to accommodate new stair wells, utility ducts, etc. Introducing openings in slabs can severely weaken the slabs due to the cut out of both concrete and reinforcing steel. There are several traditional approaches to strengthen RC slabs with openings cut out including use of steel sections, embedding reinforcing steel bars next to the opening, and the addition of columns at the edges of the openings. However, these traditional approaches can be cumbersome, expensive, and may require significant usable floor space. Recent studies, Casadei et al. (2003) and Zhao & Tan (2003) investigated the use of Carbon Fiber Reinforced Polymers (CFRP) systems to enhance the capacity of one-way RC slabs with openings. The studies concluded that externally bonded CFRP strengthening systems enhanced the stiffness and load-carrying capacity of slabs with an opening. However, it was recommended that effective anchorage measures should be taken to improve the strengthening system.

Hence, the aim of this study was to investigate the use of CFRP strengthening alternatives including anchored systems to restore the flexural capacity of the RC slabs with large openings in the positive moment region. Tests were conducted on RC slabs of an existing building that was scheduled for demolition. Testing a real structure allowed incorporating factors and boundary conditions that typically cannot be simulated in laboratory testing. However, testing real structures also presented challenges associated with field testing.

2 EXPERIMENTAL PROGRAM

2.1 *Building characteristics*

The RC building used for testing was located in Savannah, Georgia, USA and was scheduled for demolition on December 15, 2007. The 15-storey building was constructed in the 1970s using precast concrete walls supporting a one-way RC floor system.

Based on the construction drawings and measurements made after creating the openings, the RC slabs were 115 mm thick with a clear span between supporting walls of 3353 mm. The bottom reinforcement consisted of an orthogonal welded wire mesh (WWM) of 6 mm diameter smooth bars spaced at 102 mm. The same mesh was used for the top reinforcement; however, the top mesh only extended 914 mm from the face of the supporting wall. The clear concrete cover of the bottom and top meshes was 19 mm. Three samples of the steel mesh were tested and the average yield strength was determined to be 586 MPa. The concrete properties were determined using three cores and the concrete was found to be semi-lightweight concrete with a density of 1860 kg/m^3 and an average compressive strength of 17.5 MPa.

2.2 *Test slabs*

A total of five tests were carried out within the same floor at different non-adjacent bays with four tests conducted on slabs with openings as shown in Figure 1. The first test was performed on the original slab without openings to determine the actual flexural capacity of the slab. The second test was conducted on a slab with an opening, but without strengthening to quantify the effect of the opening. Three tests were conducted on slabs with openings using different CFRP strengthening techniques. The openings were 610 x 610 mm and were created by saw-cutting the slabs through the full depth along carefully defined lines. The layout of the five tests on the floor plan is shown in Figure 1.

The three strengthening techniques investigated in this study are externally bonded (EB) CFRP laminates, EB CFRP laminates with CFRP anchors, and Near Surface Mounted (NSM) CFRP strips. Details of FRP anchors can be found elsewhere (Lam & Teng 2001). Based on the manufacturer data sheet, the CFRP strips used in this study had a mean tensile strength of 3100 MPa, mean modulus of elasticity of 165 GPa, and ultimate strain of 1.69%.

For the third test, the NSM strips were 1.2 mm thick, 12 mm deep, and 1321 mm long with two strips applied on each side of the opening, aligned along the short span of the slab. For the fourth test, the EB laminates were 50 mm wide, 1.2 mm thick, and 1321 mm long with an orientation similar to the NSM strips. For the fifth test, six CFRP anchors were used along each EB laminate (three anchors near each end). The anchors in the CFRP Laminates were 76, 229, and 381 mm from each end of the laminate. Figure 2 shows a schematic diagram of the details of the strengthening systems used as well as a picture of the CFRP anchors after installation.

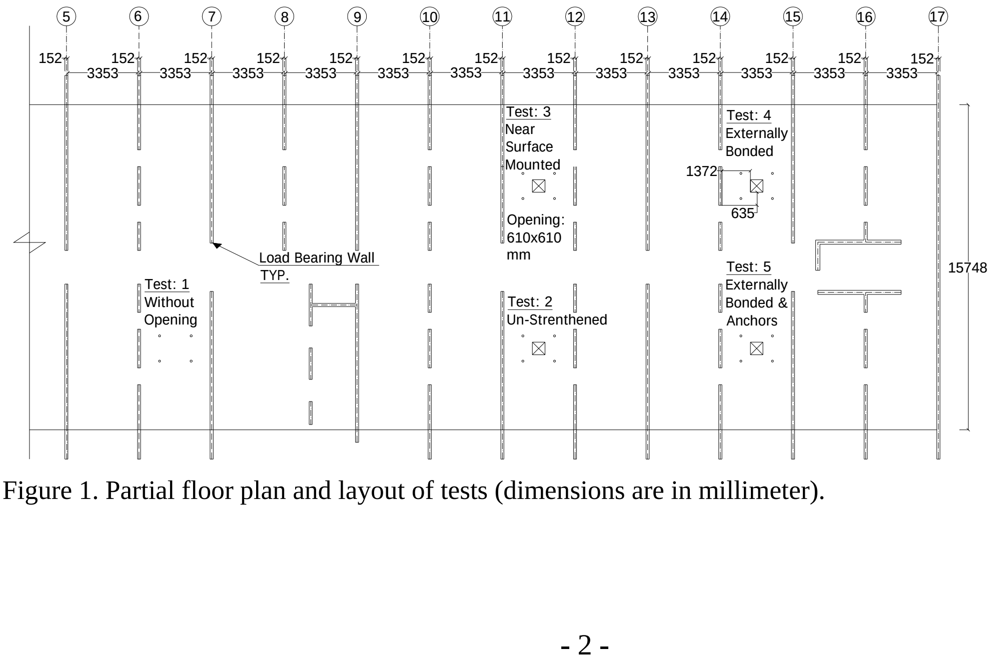

Figure 1. Partial floor plan and layout of tests (dimensions are in millimeter).

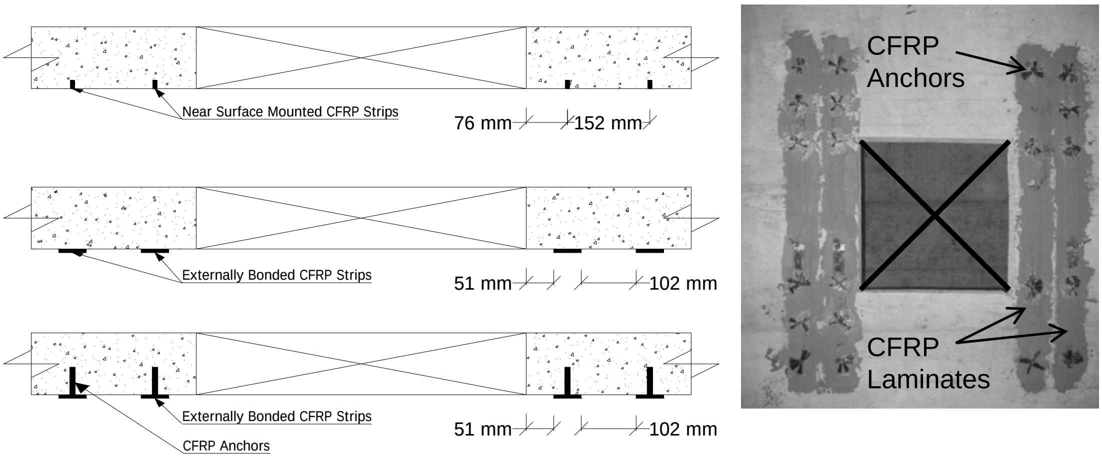

Figure 2. Schematic diagram of the strengthening systems used and the CFRP anchors after installation.

2.3 *Test setup*

In the short direction, the slabs were tested in a four-point bending configuration to develop a constant moment zone where the openings and the strengthening systems were located, as shown in Figure 3. In the long direction, the slabs were loaded at eight points to simulate line loads on opposite sides of the opening, as shown in Figure 4. The load was applied using four hydraulic jacks, connected in parallel to the same pump, that were reacting against the concrete walls at the lower floor (see Fig. 3). The applied load was measured by 133 kN load cells mounted on the hydraulic jacks. Displacements were measured at twelve points using string potentiometers (see Fig. 4). A total of twelve strain gages of 6 mm gage length were attached to the CFRP strips before installation. For NSM and EB strips, the strain gages were located at 279 mm from the middle of the strips, while for the strips used with anchors, the strain gages were located at 203 mm from the middle of the strips.

The slabs were subjected to cyclic loading, involving cycles of loading and unloading as shown in Figure 5, which is based on the loading protocol of ACI 437R-03 (2003).

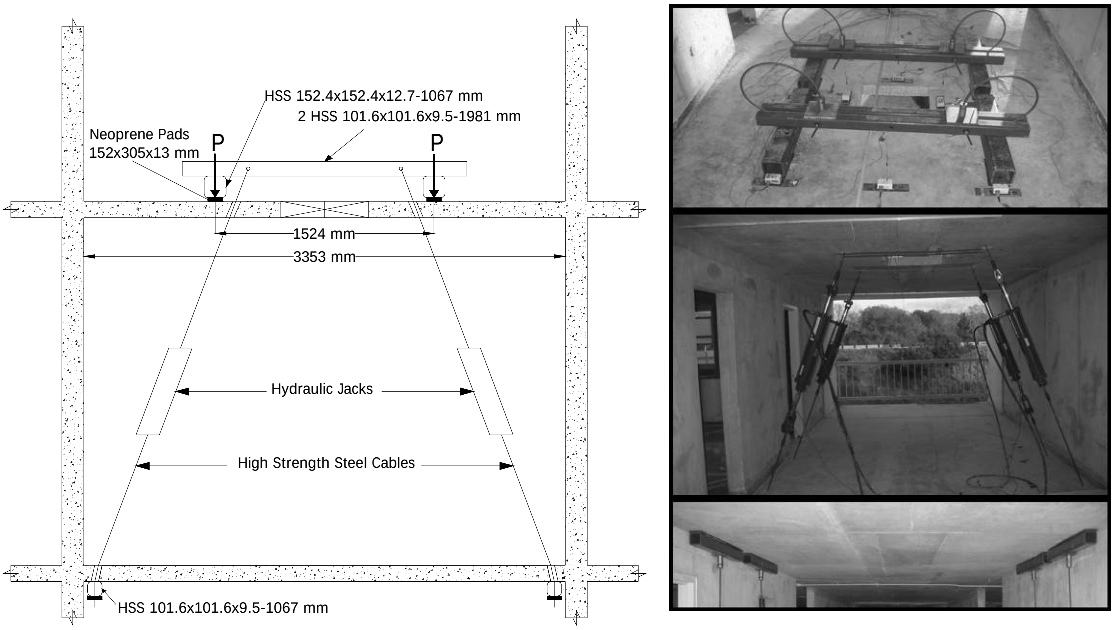

Figure 3. Cross-sectional elevation of the test setup.

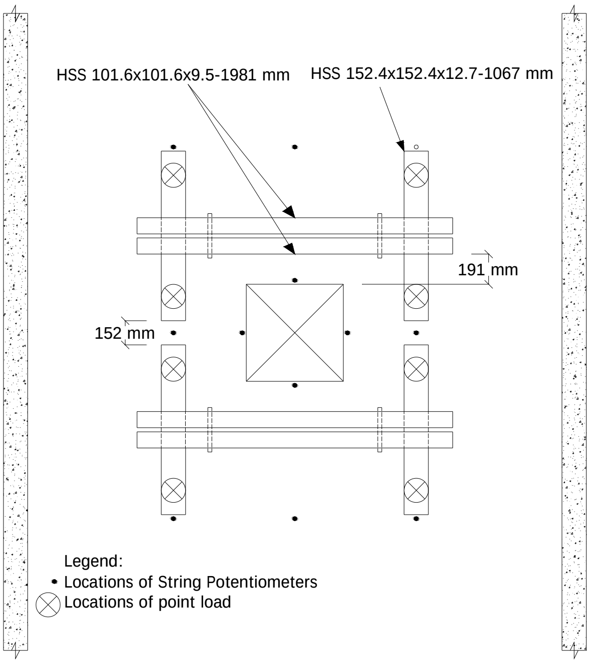

Figure 4. Plan view of the test setup and locations of the measured deflections.

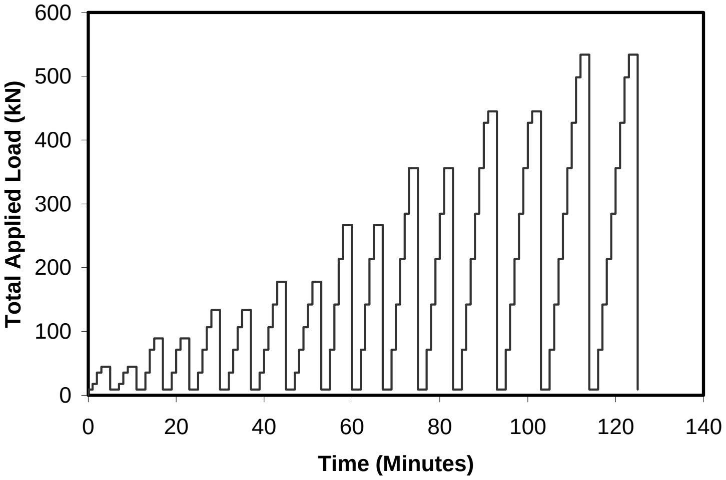

Figure 5. Cyclic loading protocol.

3 EXPERIMENTAL RESULTS AND TEST OBSERVATIONS

The efficiency of each strengthening technique was evaluated in light of the load-deflection behavior of the slab and the ultimate load-carrying capacity. As the slabs were subjected to cyclic loading, the envelope of the load-deflection curves only is presented herein. A typical load-deflection response is shown in Figure 6 for the third test of the slab strengthened using NSM CFRP strips. The plotted deflection is measured at mid-span of the slab adjacent to the opening (see Fig. 4). The load-deflection envelopes for the five tests are shown in Figure 7, and the ultimate load-carrying capacities for the five tests are summarized in Table 1. It should be noted that the fifth test (slab strengthened with EB laminates and anchors) was terminated due to rupture of the loading cables and not due to failure of the test slab.

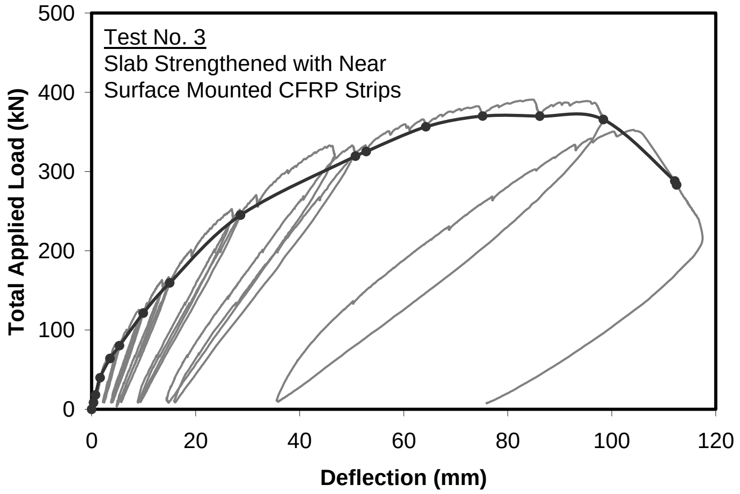

Figure 6. Load-deflection response of slab strengthened with NSM strips.

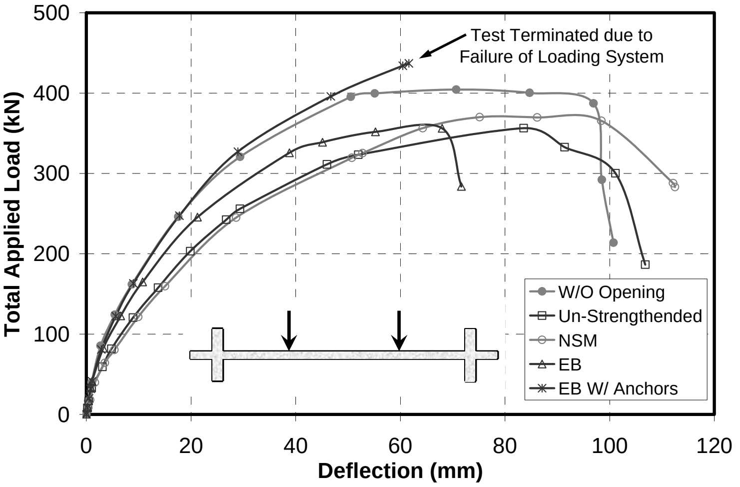

Figure 7. Load-deflection envelopes of test slabs.

All tested slabs experienced flexural failure. Flexural cracks started at mid-span, and then developed diagonally from the corners of the openings. Despite the slab being designed as a one-way system; cracks in the longitudinal direction were observed, indicating two-way bending action of the slab. This behavior was expected due to the continuity provided in the longitudinal direction.

It is evident from Figure 7 and Table 1 that creating an opening in the slab reduced its strength by 18 % without affecting the displacement capacity at ultimate. As expected, the presence of the opening reduced the stiffness of the slab. At a service load of 264 kN, which is 65% of the ultimate load of the slab without opening, the deflection was 32 mm in comparison to 20 mm for the slab without opening. Strengthening the slab with NSM CFRP strips restored 10% of the capacity of the slab without increasing the stiffness of the slab. Strengthening the slabs with EB CFRP laminates slightly increased its load-carrying capacity, achieving only a 6% increase over the un-strengthened slab and reduced its ultimate deformation due to debonding of the strips. However, the use of the EB strips significantly enhanced the stiffness of the slab because of the rigidity of the EB laminates, where the deflection was reduced from 32 mm for the un-strengthened slab to 25 mm at the service load of 264 kN. Use of CFRP anchors with the EB laminates prevented complete detachment of the laminates, and allowed the slab to restore its full flexural capacity. Furthermore, the use of anchors with the EB laminates greatly enhanced the stiffness of the slab restoring it to that of the slab without an opening. It is worth mentioning that the test was terminated due to rupture of the loading cable and not due to failure of the slab or the strengthening system. Therefore, the effect of using CFRP anchors with the EB strips on the deformation capacity of the slab could not be determined from the test results.

The slabs strengthened with the NSM strips and EB laminates failed by intermediate crack (IC) debonding of the FRP. The NSM strips restored more of the flexural capacity using significantly less FRP compared to the EB laminates. This is expected due to the enhanced bond strength of NSM strips compared to EB laminates, which is related to the confinement provided by the surrounding concrete cover delaying the IC debonding.

Table 1. Summary of test results.

	Strengthening technique	Ultimate load (kN)	Percentage of slab without opening (%)
Test No. 1	Without Opening	404	100
Test No. 2	Un-strengthened	332	82
Test No. 3	NSM	372	92
Test No. 4	EB	356	88
Test No. 5	EB with anchors	436	108

4 CONCLUSIONS

Based on the experimental results and test observations the following conclusions can be drawn:

- The slab strengthened with NSM CFRP strips had a higher load-carrying capacity in comparison to the slab strengthened with EB CFRP laminates while using significantly less area of FRP. This behavior is attributed to the improved resistance of the NSM technique to IC debonding. The use of NSM strips did not enhance the stiffness of the slab due to the small cross-sectional area of FRP used.
- The use of EB CFRP laminates slightly increased the flexural strength of the slab with opening, while significantly enhancing its stiffness. The low IC debonding capacity of the EB CFRP laminates reduced the ultimate deformation at failure due to debonding.
- Use of anchors with the EB laminates prevented complete detachment of the laminates, and thus enabled the slab to restore its full flexural capacity. In addition, the stiffness was increased reaching that of the original slab without opening.

5 ANCKOWLDEGEMENT

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