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STRENGTHENING OF PRESTRESSED HOLLOW CORE SLABS WITH OPENINGS USING NSM-CFRP STRIPS

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Precast, prestressed, hollow-core (HC) slabs are extensively used in many structures such as parking garages, commercial and industrial buildings. It is common for such structures to undergo changes while still in service, which may result in a reduction of their strength. One of these changes is to add in-situ openings at different locations along the slab to accommodate services such as intake/exhaust ducts or utility conduits. Near surface mounted (NSM) strengthening technique has proved to be an adequate technique that can be employed to restore or enhance the performance of the original structure. In this paper, the effect of openings and the efficiency of using NSM carbon fiber reinforced polymer (CFRP) strips as strengthening technique are investigated. A total of three full-scale prestressed HC slabs were tested; one without opening, one with an opening in the pure flexural zone and one with strengthened opening. Test results showed the presence of opening along the flexure span had a significant adverse effect on the post-cracking flexural stiffness, cracking load and the ultimate capacity of the slab. However, strengthening the opening with two strips of NSM-CFRP effectively enhanced the post-cracking stiffness, increased the ductility of the member and restored the flexural strength deficit incurred as a result of cutting the opening, and provided a net increase in flexural capacity.

Keywords: Near surface mounted, High strength concrete, Carbon fiber reinforced polymer (CFRP), Restoration, Post-cracking stiffness, Ductility, Flexural capacity.

1 INTRODUCTION

Precast prestressed hollow core (HC) slabs are extensively used in many structures such as parking garages and commercial and industrial buildings. It is common for such structures to undergo changes while still in service, which may result in a reduction of their strength or require them to resist an increased applied load. One of these changes is to add in-situ openings in several locations within the slab span to accommodate intake/exhaust ducts along industrial building roofs, or utility conduits along parking garage floors. Strengthening techniques are commonly employed to restore or enhance the performance of the original structure. Near surface mounted (NSM) strengthening technique, using FRP composites, has proved to be an adequate technique to strengthen reinforced concrete (RC) structures (De Lorenzis and Nanni 2002, El-Hacha and Rizkalla 2004, Teng *et al.* 2006). The non-corrodible and durable nature of fiber reinforced polymer (FRP) composites can successfully mitigate the effects of inclement conditions, and effectively improve the structures performance.

The behavior of one-way and two-way RC slabs with openings strengthened with FRP materials has been previously studied (Tan and Zhao, 2004, Enochsson *et al.* 2007, Smith and Kim 2009, Seliem *et al.* 2011). Both externally bonded (EB) laminates or NSM strips were used to strengthen these slabs. It was found that providing CFRP strengthening for slabs with openings effectively enhanced the stiffness and the ultimate load capacity of the slab where comparable behavior to the control slab was observed. On the other hand, the carbon (C) FRP strengthened slabs exhibited a brittle failure in contrast to a more ductile behavior for the unstrengthened slabs (Tan and Zhao 2004). Also, it was reported that all slabs with CFRP strengthened openings exhibited an increased load-carrying capacity compared to their counterparts without strengthening (Enochsson *et al.* 2007). Moreover, slab with opening strengthened with NSM-CFRP strips reached 92% of the slab capacity (compared to 82% in slab with unstrengthened opening); however, the NSM strips were ineffective in restoring the stiffness of the slab (Seliem *et al.* 2011). This study represents, up to the authors' knowledge, the first attempt to investigate the behavior of prestressed HC slabs with openings unstrengthened and strengthened with NSM-CFRP strips.

2 EXPERIMENTAL PROGRAM

2.1 Test Specimens

Three full-scale prestressed HC slabs were tested to failure. All slabs had a thickness of 203 mm with a concrete gross sectional area of 140,194 mm^2. The slabs had originally an internal prestressing steel reinforcement ratio of 0.00274 (7-9 mm strands). The test specimens include one slab without opening to serve as reference, one slab with opening located at mid-span along the constant moment region and one slab with identical opening strengthened with NSM CFRP strips. The opening had a rectangular shape measuring 308 × 600 mm. It is worth mentioning that the middle strand was cut in slabs with openings. Details of test specimens are shown in Fig. 1.

2.2 Materials

Normal weight, high-strength concrete with a target compressive strength of 28 MPa at 18 hours and 45 MPa at 28 days were used to cast the specimens. The compressive strength, at the day of testing for each slab, is listed in Table 1. The internal prestressing reinforcement was 7-wire low-relaxation high-strength steel strands. The strands were of grade 1860 and were initially stressed to $0.75 f_{pu}$. CFRP strips (2×16 mm rectangular section) were used to strengthen the specimens. The laminates had a modulus of elasticity of 131 GPa and an ultimate tensile strength of 2068 MPa. The structural adhesive used to bond the NSM-CFRP laminates to the concrete substrate was Kemko 038 with a tensile strength of 62 MPa, and a flexural modulus of 38 GPa.

2.3 Cutting Openings and Strengthening Procedure

A hand-held saw was used to cut the openings and the longitudinal grooves along the inverted soffit of the slabs. The longitudinal grooves were terminated 200 mm from each support. The target depth of the grooves was 22 mm while the thickness was 6 mm. After cutting the grooves, the structural adhesive was injected along the groove, using specialized mixing and dispensing equipment until the groove was ¾ full, leaving an adequate space for the CFRP laminate. Strips then were pushed into grooves, in a vertical orientation with the larger dimension perpendicular to the concrete surface.

Table 1. Details of test specimens.

Specimen	**Concrete strength (MPa)**	**Internal Reinforcement**		**Opening Location**	**Number of CFRP Laminates**
		Configuration	Ratio		
S1	64.0			None	None
S2	64.0	7 No. 9	0.00274	Flexure span	None
S3	56.5			Flexure span	2

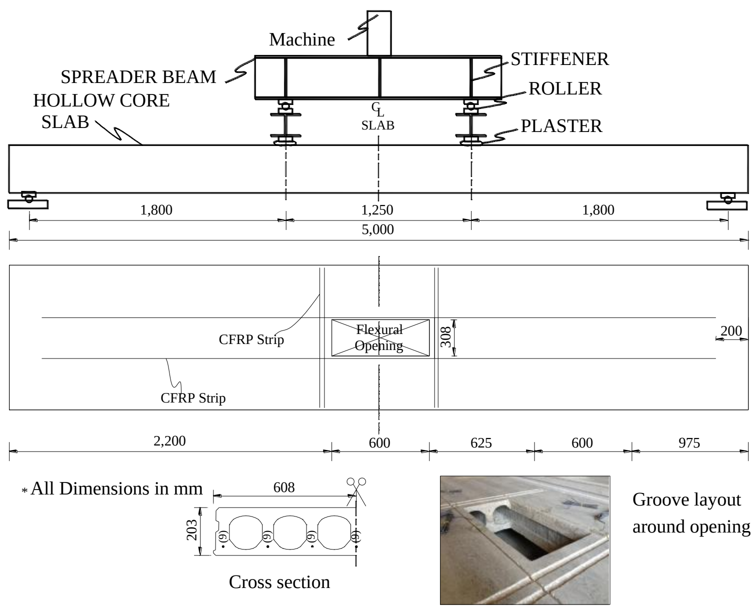

Figure 1. Details of test setup, opening location, cross section and groove layout.

2.4 Test Set-up and Instrumentation

The slab specimens were subjected to four-point bending up to failure. Figure 1 illustrates a schematic drawing of the test setup components along with key dimensions.

A 5000-kN MTS hydraulic machine was used to apply a concentrated load on a rigid system of steel spreader beams that was used to deliver a distributed line load along the full width of the slab. The slabs had a clear span of 4,850 mm, divided into a constant bending moment zone and two shear spans. During testing, the load was applied at a stroke-controlled rate of 1.0 mm/min and was increased to 2.0 mm/min after cracking.

Linear variable displacement transducers (LVDTs) were used to monitor deflection along the span length of each specimen. Also, electrical strain gauges were installed on the internal steel strands and the NSM-CFRP reinforcement to measure the induced tensile strains. The strain gauges were attached to the steel strand in one side of the opening and to the CFRP strip in the other side of the opening. A data acquisition system monitored by a computer was used to collect readings of the instrumentation.

3 TEST RESULTS

3.1 Mode of Failure

Figure 2 shows photos of the mode of failure of all test slabs. The control slab (S1) and the unstrengthened slab with opening (S2) exhibited pure flexural behavior where they experienced steel yielding, followed by concrete crushing, and ultimately failed as individual steel strands began to rupture. In strengthened slab (S3), near failure, a pair of transverse strips delaminated from the concrete substrate (Failure occurred in the surrounding concrete substrate as well as the surrounding adhesive matrix). Following the delamination of the transverse strips, the longitudinal strips experienced a partial delamination failure at several locations but did not fully de-bond from the substrate. This occurred within the maximum moment zone. Further increase in the load led to the outermost tensile fibers of the CFRP strips to fray. Finally, concrete crushing was observed at failure.

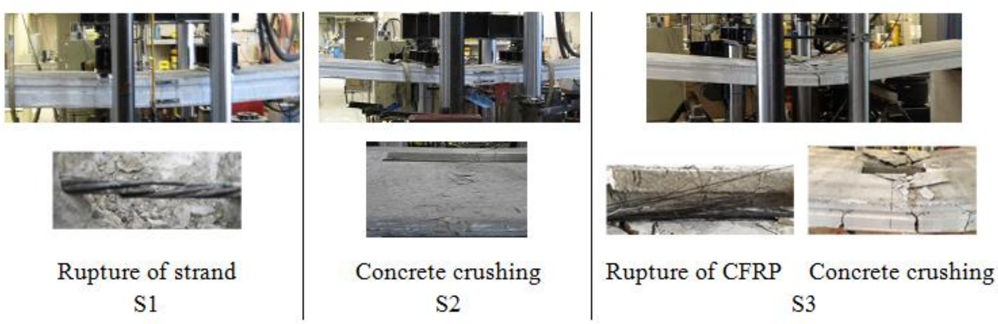

Figure 2. Mode of failure of test specimens.

3.2 Deflection

The load-deflection relationship at mid-span of the tested slabs is depicted in Fig. 3. All the tested slabs demonstrated similar behavior where the load-deflection curve can be divided into pre-cracking and post-cracking stages. The pre-cracking stage is characterized by linear relationship and small deflections in all slabs. In the post-cracking stage, excessive deformations can be seen reflecting the reduced flexural stiffness after cracking. Slab without strengthening showed large deformations without any significant increase in the load. The addition of an opening within the slab reduced the post-cracking flexural stiffness. Strengthening the opening with NSM CFRP strips improved the postcracking stiffness, as indicated by the increasing slope of the curve until failure.

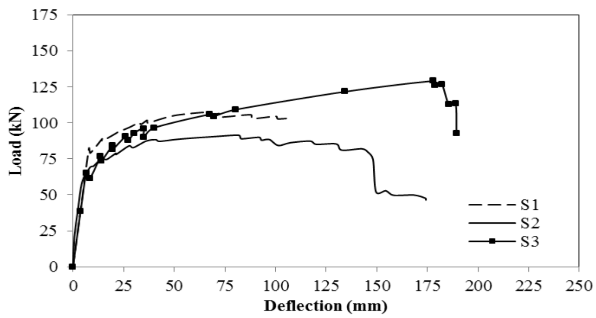

Figure 3. Load-deflection relationship of test slabs.

3.3 Strains

In general, the strains in the strands were small up to the yielding point; then, it increased rapidly until failure. In addition to the strain induced in the strands due to prestressing force, the measured strain at failure was approximately 9,920 με in slab S1 while the strains in slab S2, failed at lower load capacity, reached approximately 3,300 με. In S3, the measured strain at mid-span at failure was 10,130 με. Regarding the measured strain in the CFRP strips, it was insignificant before cracking of the slab. However, considerable increase was observed with increasing the load until failure. At failure, the measured strain at mid-span was approximately 9,370 με.

3.4 Capacities of Test Specimens

Cracking, yielding and ultimate moments for each slab are presented in Table 2. The cracking moment of the control specimen was approximately 73 kN.m. In slabs with openings (S2 and S3), the cracking moment decreased significantly, by approximately15%. The moment corresponding to yielding of strands was approximately 80 kN.m for slab S1; however, it decreased by 13% in the unstrengthened slab with opening (S2). Strengthening the opening enhanced the yielding moment slightly by 8% (form 71 kN.m in slab S2 to 77 kN.m in slab S3).

The presence of an opening in the pure flexural region decreased the ultimate capacity 17% when compared to the control specimen. On the other hand, strengthening openings with two strips of NSM-CFRP effectively restored the flexural strength deficit incurred as a result of cutting the openings. The addition of strengthening reinforcement resulted in a significant capacity enhancement of 40% compared to slab with unstrengthened opening while this increase is approximately 23% higher the capacity of the reference slab without opening.

Table 2. Summary of test results.

Specimen	Cracking moment, (kN.m)	Yielding Moment, (kN.m)	Ultimate Moment, (kN.m)
S1	73.0	80.0	97.0
S2	62.0	71.0	83.0
S3	63.0	77.0	116

4 CONCLUSIONS

Based on the limited test results presented above, the following conclusions can be drawn:

1) The presence of an opening in the flexural zone of prestressed hollow-core slab decreased the cracking load, the post-cracking stiffness and the load at failure.
2) Slab with an opening exhibited similar failure mode to that observed in the reference slab without openings. This could be attributed to the presence of the opening in the constant bending moment region.
3) Strengthening the opening with two strips of NSM-CFRP not only restored the flexural strength deficit incurred as a result of cutting the openings but provided additional flexural capacity.

It is worth mentioning that more experimental work is required to verify these findings.

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