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Efficient near surface mounting CFRP strengthening of pretensioned hollowcore slabs with opening – An experimental study

Sameer Kumar Sarma Pachalla, S. Suriya Prakash *

Department of Civil Engineering, Indian Institute of Technology Hyderabad, India

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ABSTRACT

Carbon fiber reinforced polymers (CFRP) are commonly used in strengthening of civil infrastructure due to their superior mechanical properties. Near surface mounting (NSM) of CFRP laminates is an efficient strengthening scheme to restore the capacity of concrete elements. Hollowcore slabs are pretensioned precast concrete elements reinforced only with prestressing strands. Due to various service requirements, openings/cut-outs are provided in the slabs. Reinstating the capacity of hollowcore slabs lost due to the presence of openings is very important as openings can severely reduce the capacity of these slabs and alter the load distribution in the floor system. This paper investigates the efficiency of NSM technique using CFRP laminates in restoring the capacity of hollowcore slabs with openings. Ten full scale hollowcore slabs were tested at two shear span to depth (a/d) ratios and with two different locations of opening. Presence of opening reduced the ultimate capacity of slab by 44% and NSM CFRP strengthening fully restored the lost capacity based on a/d ratio. The adopted strengthening was more effective in shear dominated than in flexure dominated specimens. However, in both a/d ratios, good improvement in initial stiffness was observed due to NSM CFRP strengthening.

1. Introduction

Strengthening of concrete elements is generally required to restore the strength of damaged elements or to increase its existing capacity. Reasons for strengthening include deterioration of concrete or steel, increased loads, provision of openings and for correction of major design/construction errors. Strengthening can be done by various methods such as (i) adding an additional layer of concrete and reinforcement (concrete jacketing), (ii) attaching steel plates and (iii) Using fiber reinforced polymers as additional reinforcement. Out of the techniques available, fiber reinforced polymers (FRP) have gained much prominence in strengthening concrete structures due to their superior mechanical properties such as high tensile strength, high stiffness, low weight, ease of application and improved durability [1]. FRP materials made out of glass, carbon or basalt, etc., which are commercially available in the market can be used for strengthening.

Applicability and evaluation of FRP materials in the field of civil engineering started in the early 90's [2–5] and is one of the most researched topics in present days. Strengthening using FRP materials can be done by two techniques, namely external bonding (EB) and near surface mounting (NSM). The external bonding technique involves adding thin layers of FRP composite to the external surface of concrete using adhesives whereas NSM technique involves fixing of FRP laminates in the pre-cut grooves using adhesives. In both the techniques, two component epoxy materials are generally used as adhesives. Near surface mounting technique (NSM) is proven to have many advantages over the external bonded method such as (i) reduced surface preparation during installation, (ii) less chances of debonding and (iii) better protection to FRP due to less exposure to external conditions [1]. Use of carbon fiber reinforced polymers (CFRP) for NSM technique is most viable because of higher tensile strength and elastic modulus of the material when compared with glass fiber reinforced polymers (GFRP). These properties cause the lesser usage of FRP and smaller groove size, which in turn leads to easier installation with lesser risk of interfering with the internal reinforcement. Reduced groove size also requires lesser epoxy filler material and results in reduced installation time. Considering these advantages, carbon fibres and NSM technique were chosen for the strengthening of hollow core slabs in this study.

Use of CFRP for the strengthening of reinforced concrete (RC) beams and prestressed (PC) beams by NSM technique is very well documented [1,6–11]. Previous research has confirmed that the

* Corresponding author.
E-mail addresses: ce13p1007@iith.ac.in (S.K.S. Pachalla), suriyap@iith.ac.in (S.S. Prakash).

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NSM reinforcement improves the ultimate and yielding strength, as well as the post-cracking stiffness [1]. Some studies have also focused on strengthening of RC slabs using CFRP [12–15] and found similar trends in results as that of beams. The authors have previously found that openings significantly affect the behaviour of hollow core slabs [16] and suitable strengthening has to be carried out to reinstate the lass of load carrying capacity. Use of CFRP is preferred in strengthening of prestressed concrete elements due to their high stiffness and strength compared to GFRP. Some previous investigations have focused on the both experimental and numerical analysis of concrete elements strengthened with NSM technique [17–20].

Hollowcore slabs are precast pretensioned concrete elements with prestressing strands as the only reinforcement. Other reinforcement cannot be provided because of the casting process of these slabs. Hollowcore slabs are cast by extrusion process. Extrusion of slabs is a casting process in which the wet concrete (zero slump) is extruded through the dies of the machine. The machine moves on the fixed rails and casts the slabs with cores. After extrusion, the slab retains its shape due to zero slump. Longitudinal cores are provided along the length of the slab primarily to reduce the dead weight and make the cross section efficient for prestressing. The hollowcore slabs are generally constructed as simple supported elements and the width to length ratio makes these slabs behave as one way slabs. Hollowcore slabs are typically used as slab elements in buildings apart from their use as wall panels. To accommodate various building services, it is very common to have openings in slabs and wall panels. Openings cause disruption in the load distribution paths and also make the slabs as weak links in the whole structure requiring special attention in both analysis and design. Even though openings are pre-planned during the design phase, in many situations they are provided after construction in locations where necessary design precautions were not taken. Openings in hollowcore slabs could coincide with the location of strands and this may lead to its curtailment. Reduction in the area of prestressing reinforcement can significantly impact the strength and stiffness of hollowcore slabs [16]. In such situations, strengthening of slabs to restore the original capacity is very important. The main aim of this experimental study is to evaluate the efficiency of flexural strengthening of hollowcore slabs with openings by NSM technique using CFRP laminates. Only flexural strengthening of slabs was done and no U-wraps were provided to increase the shear capacity of the slabs.

The effect of openings on the behaviour of reinforced concrete (RC) slab elements was studied by various researchers in the past. Afefy and Fawzy [22] carried out an experimental investigation on one way RC slabs with openings and found that the ultimate strength and deflection reduced by 50% and 45% respectively due to the provision of openings. They noted that the decrease in ultimate strength was not directly proportional to the reduction in width of section due to opening. Al-hafiz et al. [23] carried out experimental studies on one way RC slabs with thickness ranging from 40 mm to 80 mm with a cut-out width of 19% of the width of the slab. They found that the ultimate strength decreased from 34% to 38%. Further, it was observed that the thickness of slabs played a major role in the reduction of ultimate strength due to openings. Anil et al. [24] studied the effect of width of opening located at both flexure and shear zones. Due to higher shear span (a) to depth (d) ratio ($a/d = 7$) used in the study, the effect of opening was more prominent when the opening location was in flexure zone. They reported that the openings in flexure zone reduced the ultimate strengths by 24–44%. In general, it was observed that the strength and stiffness reduction was not proportional to reduction in width of slab due to opening. They also noted that there was a change in failure mode depending on the location of the openings.

Strengthening of hollowcore slabs using CFRP fabric and strips was also studied by [25,26] several researchers in the past. Both the fabric and strips increased the capacity of the slabs by about 80% when compared with control specimens. No previous work has focused on the effect of openings on hollowcore slabs and on the efficiency of NSM CFRP strengthening in restoring the lost capacity due to openings. The present study tries to fill in the knowledge gap existing in this area.

2. Experimental investigation

2.1. Overview

Ten full scale specimens were tested to evaluate the effect of openings in hollowcore slabs and to assess the efficiency of NSM strengthening technique using CFRP laminates in restoring the capacity of hollowcore slabs with openings. All the slabs were 150 mm deep, 1200 mm wide and 3500 mm long as shown in the Fig. 1. All the slabs were cast on the same day and were cured at the same temperature. The slabs were prestressed with six numbers of strands of 9.53 mm diameter with a prestressing jacking force of 70 kN each. Two shear span to depth ratios (a/d) of 3.5 and 7.5 were selected for the test program to evaluate the behaviour under different bending moment to shear force ratios. A schematic diagram of test setup defining the shear span to depth ratio is shown in Fig. 2. The slabs were grouped into two series based on the a/d ratio. The test matrix shown in Table 1 summarizes the specimens and study parameters of the test program. Two slabs were tested as control specimens without openings at each a/d ratio of 3.5 and 7.5. Other slabs had one opening of size 300 mm $\times$ 600 mm (25% of the width of the slab) which was provided during casting. The opening could be at the mid span location (Flexural Opening-FO) or in shear dominated zone (Shear Opening-SO). All the openings coincide with the axis of symmetry along the width of slabs. The openings were provided at the mid span and shear span locations to evaluate its effect on the flexural and shear capacity of the slabs. Typically, openings are provided close to supports (closer to column lines) for various mechanical and electrical provisions. In some instances, it may be required to provide openings at the mid-span either for services or for structural purposes. Therefore, these locations were selected to reflect the worst effect of openings. The size of the openings was chosen based on the discussions with local slab manufacturers and standard industry practices. The plan view of the slabs with locations of opening is shown in Fig. 1. Two prestressing strands located at the middle of the cross section were cut because of the opening. The cross sectional properties of sections at the opening and at normal location are given in Table 2.

2.2. Material properties

All specimens were cast using normal weight, ready-mix concrete with 10 mm nominal coarse aggregates. Zero slump concrete with target compressive strength of 40 MPa was used for casting. The slabs were cast using an extrusion process. The mix design of concrete used for casting is shown in Table 3. The unit weight of concrete was about 2400 kg/m^3. The tested average concrete cube (150 mm cube) strength was 42 MPa on test day with standard deviation of 0.7 MPa. Seven-wire low-relaxation strands (9.53 mm diameter) with an ultimate tensile strength of 1860 MPa and modulus of elasticity of 196.5 GPa were used for prestressing. Strands were placed in the tension side of the slab with a jacking force of 70 kN each. Carbon fiber reinforced polymer strips used for strengthening of the slabs were tested in universal testing machine (UTM) as per ATSM D3039 [27] to evaluate the