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A STATE-OF-THE-ART REVIEW ON STRENGTHENING OF REINFORCED CONCRETE SLABS WITH OPENINGS

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ملخص البحث:

يوجد كثير من التقدم والتطورات في تكنولوجيا الخرسانة التى لها تأثير كبير في النظم الإنشائية. يعرض هذا البحث طرق التدعيم المختلفة التى تستخدم في تدعيم البلاطات الخرسانية وخاصة البلاطات الخرسانية المفرغة سابقة الصب سابقة الإجهاد بالإضافة الى الأبحاث السابقة المتعلقة بعمل الفتحات الغير متوقعة وتأثيرها على البلاطات المفرغة سابقة الصب سابقة الإجهاد. حيث ركزت الدراسات السابقة المتعلقة بالبحث على سلوك البلاطات في الانحناء والقص وتم عرض الخلاصة من الأعمال السابقة في هذا البحث.

ABSTRACT

There are many developments in concrete technologies that have major impacts on structural systems. This review represents different strengthening techniques used in strengthening of hollow core slabs (HCS) in addition to previous research works relating to effect of making unforeseen openings in prestressed precast hollow-core slabs. Previous studies related to the present research focused mainly on flexural and shear behavior of hollow core slabs with openings. The main conclusions obtained from previous researches are also included in this paper.

1. INTRODUCTION

Precast prestressed concrete Hollow-Core (HC) slabs have been used in many civil engineering structures including residential and commercial buildings, parking structures, and short span bridges [1]. A HC slab consists of 40–50% voids running along the length of slab to reduce its self-weight and thereby leading to economy in construction as shown in Fig. 1. HC slabs have an important market presence in many countries. Prestressed reinforcement improves the serviceability performance of HC slabs compared to plain slabs (those without voids), increasing the cracking moment as well as the load-bearing capacity. Span lengths of up to 16 m and high loads levels can be achieved with HC slab floor systems [2, 3].

Figure 1: Precast prestressed hollow core slabs

HC slabs have been used for several years. In the early years of their appearance in the industry HC slabs were made by many different systems. Some were produced in fixed forms and some in movable forms. The variations were mostly in the coring system. Nowadays, the large-scale expansion of the construction industry created the need for more efficient and economical ways to produce HC slabs. The technology which is now used is producing by extruding technology in large longitudinal forms. When the concrete is sufficiently hardened, the panels and strands are cut to the appropriate length which may vary to whatever dimension the customer requirements. This process excludes the use of any shear reinforcement and the strands are anchored only by bond [4,5].

It is common to have openings in the slabs for various structural reasons, such as provision of columns or for facilitating the installation of mechanical, electrical, and plumbing services. Some of these openings are taken in design consideration before manufacturing, the common method of designing hollow-core slabs with openings is to provide additional strands equal to the number of strands cut for the opening. These strands are either provided in the adjacent webs or distributed uniformly in the remaining cross section.

The other type is unforeseen openings, which can be made due to change in architecture plans or change of usage. These openings reduce the capacity of hollow-core slabs significantly making these slabs a weak link in the whole assembly. Therefore, they require special attention in both analysis and design.

Some researchers studied the effect of opening on the behavior of the hollow core slabs in flexure and shear, and used different strengthening techniques to regain the capacity of hollow core slabs and enhance their behavior in shear and flexure.

2. NECESSITY OF STRENGTHENING REINFORCED CONCRETE SLABS

Strengthening is known as the process of increasing the performance of members or structures more than the initial performance that the structure or the member were designed on it. Strengthening of concrete elements is generally required to restore the strength of damaged elements or to increase the existing capacity. Reasons for strengthening include deterioration of concrete or steel, increased loads, provision of openings and for correction of major design/construction errors [6].

3. STRENGTHENING TECHNIQUES FOR SLABS WITH OPENINGS

If openings are taken in consideration in designing for new structures, we must consider the proper detailing of additional reinforcing steel in the slab or beams, or thickening of portions of the slab around openings. In case of existing structures, the way we deal with opening could change. First, it must be calculated if the structure can accommodate new openings without strengthening. If strengthening is requested, the situation becomes more difficult and strengthening techniques must be considered.

3.1. USING EXTERNALLY BONDED STEEL PLATES

The most used method for increasing the moment capacity is to add steel plates to the surface of a slab, connected with the help of bolts or post installed anchors. Although the installation of the steel plates is rather easy it has to be considered that it must not interfere with the flooring system. When using bolts for connecting the plates, they interfere with the flooring system. Normally the plates are installed on the bottom of the slab with post-installed anchors as shown in Fig. 2. A disadvantage of this method is that overlapping difficult; thus, it works best when strengthening is required in only one direction.

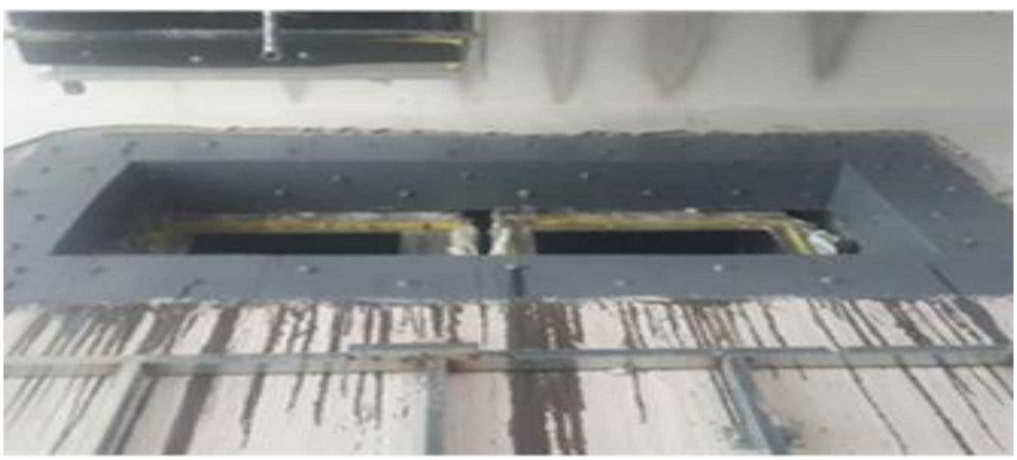


Figure 2: Strengthening using steel plates

3.2. ADDING NEW SUPPORTING ELEMENTS

Another approach is possible when existing beams are present. In this case, steel beams that span between the concrete beams can be installed as illustrated in Fig. 3. In order that this solution to be effective, non-shrink grout must be installed between the top flange of the steel beam and the bottom of the slab to ensure uniform bearing [7].

Figure 3. Strengthening using steel supporting I beams

3.3. INCREASE SLAB THICKNESS

To increase the depth of the slab, a new reinforced concrete layer should be added to the original slab to achieve the desired capacity of section and performance as shown in Fig. 4. The stages in applying this method can be described as it follows: removal of the deteriorated concrete, corrosion removal from the exposed reinforcement, surfaces cleaning and preparation to ensure bonding with the repair material, replacement or addition of the supplementary reinforcement, reinforcement protection (in some cases), applying of the repair material. The main disadvantages of such system are the reduction in the floor clear height after the depth increasing and the need to construct a new formwork.

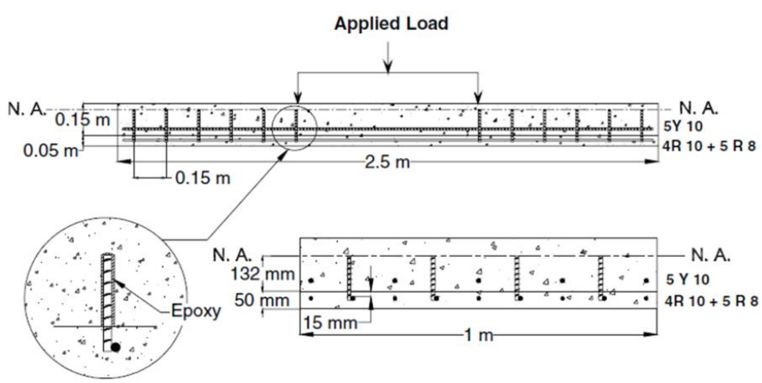
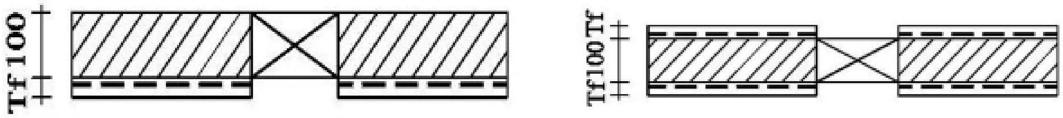


Figure 4. Section enlargement technique

3.4. FERROCEMENT LAYERS

Ferrocement can be described as a type of thin composite material made of cement mortar reinforced with wire meshes. The wire meshes are uniformly distributed in continuous layers with relatively small diameters. The Ferro cement is used, in general, to replace the damaged concrete and reinforcement (if also damaged). Strengthening with ferrocement improves cracking resistance, flexural stiffness and the ultimate loads compared to the original unstrengthened element [7]. These improvements depend on the full composite action between the Ferrocement layers. There are many advantages of ferrocement such as materials are available in most of the countries, ease of construction, less weight, and low cost of the construction materials. Ferrocement layer can be added at tension side or both tension and compression sides as shown in Fig. 5.



A) Applying ferrocement at tension side **B) Applying ferrocement as sandwich form**

Figure 5. Strengthening scheme of slabs with ferrocement

3.5. EXTERNAL POST-TENSIONING

It is very effective in increasing the flexural and shear capacity of concrete slabs. It can be applied to reinforced and prestressed concrete members. The technique is applied to reinforced concrete slabs to correct the excessive deflections and cracking but cracks must be repaired by means of epoxy injecting or other known methods before applying post-tensioning. This method has been effectively applied in bridge rehabilitation, and in all the cases it has chosen because of its advantages, being economical and requiring less time to complete. The system provides active forces and therefore was more compatible with existing constructions. Figure 6 shows strengthening of Styria bridge with external post tensioning. The post-tensioning forces are delivered by means of standard prestressing tendons or high-strength steel rods, usually located outside the original section. The tendons are connected to the structure at anchor points, typically located at the ends of the member. End-anchors can be made of steel fixtures bolted to the structural member, or reinforced concrete blocks that are cast in situ. The desired uplift force is provided by deviation blocks, fastened at the high or low points of the structural element [8].

Figure 6. Styria Bridge (Austria)

3.6. EXTERNALLY BONDED FIBER-REINFORCED POLYMER (FRP)

FRP composite materials have been successfully used in the construction of new structures and in rehabilitation and strengthening of existing structures. slabs are strengthened by bonding FRP strips at maximum positive or negative moments to increase the section capacity. The main disadvantage of this technique is early failure due to debonding. These materials hold great promise for the future of construction industry. Using FRP reinforcement in repair is a highly practical strengthening system, because of ease and speed of installation, less labor intensity, efficiency of structural repair and corrosion resistance of the materials, in addition to being quick and easy to handle on site the application of FRP poses minimal modification to the geometry, aesthetics and utility of the structure [9]. In some situations, FRP composites are the only plausible material that could be used for strengthening, especially in places where heavy machinery cannot gain access or closure of the use is not practical. The overall cost of the whole strengthening job using FRP materials can be as competitive as using conventional materials, Although the material cost of carbon FRPs was several times more than that of steel plates, the fact that 6.2kg of carbon FRPs could be used in place of 175kg of steel is sufficient to explain the advantages of FRPs over steel plates [10]. Figure 7 shows the strengthening mechanism using reinforcement steel bars and CFPR.

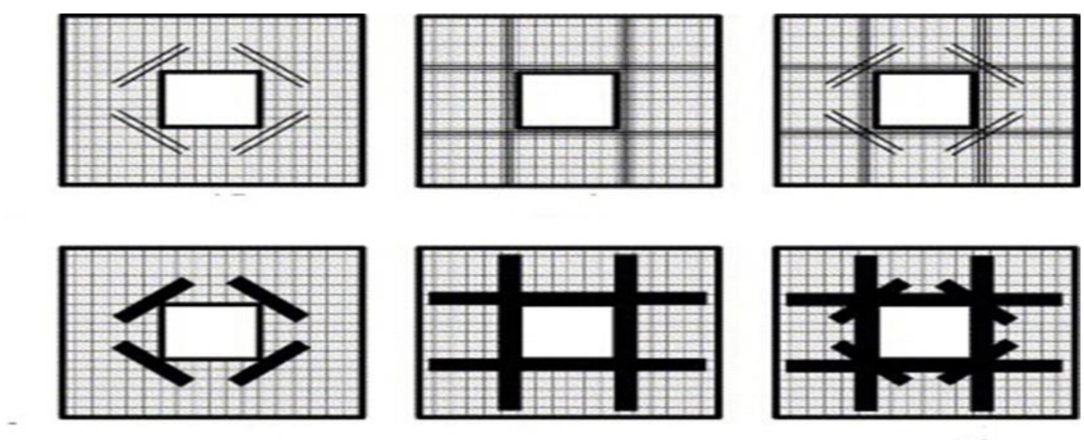


Figure 7. Strengthening techniques using embedded steel bars and carbon fiber

3.7. TEXTILE REINFORCED CONCRETE (TRC)

An alternative strengthening material that has become of interest as of late is Textile Reinforced Concrete (TRC). This composite material which consists of fiber textile as embedded reinforcement and cement mortar as resin (as shown in Fig. 8) can be used in new structures, as well as in strengthening of beams, slabs, columns and even walls. Due to its high tensile strength, TRC can be effectively used in strengthening elements in bending such as slabs or beams. It has a high tensile strength and can be effectively used in strengthening elements in bending such as slabs or beams by applying one or several layers of TRC at the bottom or top of the element which is strengthened [11].

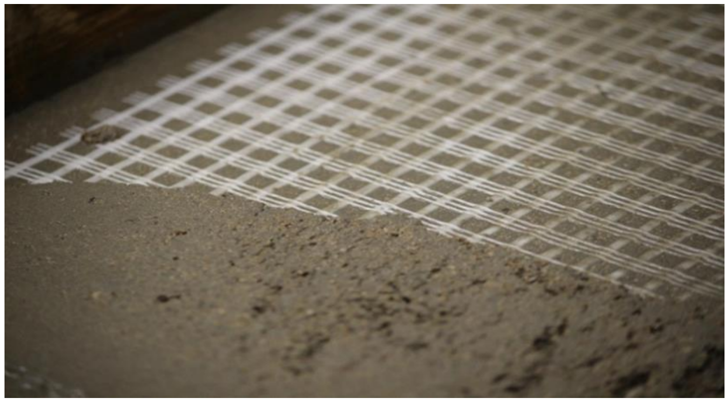


Figure 8. Textile reinforced concrete slab

3.8. NEAR SURFACE MOUNTED TECHNIQUE (NSM)

It consists of adhesive and rods. The adhesive used may be of two types epoxy or high-quality cement grout. The rods can have different section configurations, and the most commonly used are the rectangular and round sections. The strengthening technique is shown in Fig. 9.

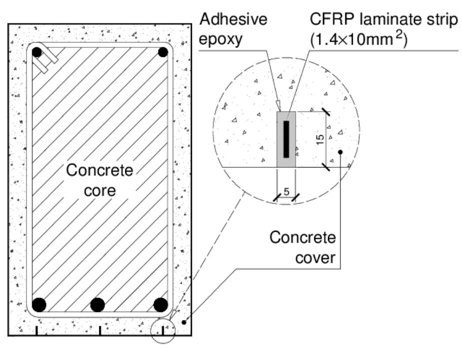


Figure 9. Strengthening details of near surface mounted using CFPR

More than one system can be used in strengthening but it should be tailored to serve the intended use for the designed service life of the structure without interfering with its functionality [12].

4. PREVIOUS STUDIES

Openings are made in slabs because of facility requirements such as the installation of air conditioning, piping ducts and fire-extinguishing systems. Although these openings are necessary in such slabs, they place a break in the continuity of the slab and reduce the capacity, stiffness, energy dissipation capacity, and ductility of the slabs. Therefore, an effective strengthening method should be adopted to increase the shear and flexural capacities of the slab with the opening. One of the traditional approaches for strengthening slabs with openings is embedding equal steel bars at the edge of the opening. ACI recommended that the opening should be confined by steel bars and half of the reinforcement interrupted must be replaced on each side of the opening. ACI 440.2R-08 [13] recommends an easy way to strengthen existing RC slabs with openings is bonding

Fiber Reinforced Polymer (FRP) sheets to the tension side of the slab around the opening [11].

H.M. Afefy et al. [14], to investigate the structural flexural performance of strengthened one-way rein- forced concrete slab included cut-out, six slabs including cut-out adjacent to the central patch load in addition to one slab without cut-out as a reference slab were tested up to failure under incremental monotonic loading. The six slabs including cut-outs contained one control un-strengthened slab along with five strengthened slabs. These slabs were strengthened using either Near Surface Mounted (NSM) steel bars or externally bonded Carbon Fiber Reinforced Polymer (CFRP) at the tension side, while four out of them were strengthened by either NSM-steel bars (one slab) or an overlay of Engineered Cementitious Composites (ECC) material (three slabs) at the compression side. It can be concluded that end anchors for the CFRP sheets along with the surface preparation before installing the ECC overlay are very important parameters in order to guarantee the optimum utilization for both the CFRP sheets and the ECC overlay material. In addition, the test results showed that the hybrid strengthening technique incorporated NSM-steel bars in tension side along with ECC overlay in compression side showed its superiority among all proposed strengthening schemes. It is not only allowed the slab included cut- out to restore its flexural resistance, but also it enabled the slab to outperform its structural performance compared to that of the slab without cut-out.

Mona Mahlis et al. [15], intended to investigate the behavior of two-way RC beamed slabs with openings introduced after casting through testing ten square reinforced concrete two-way beamed slabs. They were divided into two cases: (Case A), and (Case B). Case A consisted of five slabs cast with a square 300 mm side opening in the mid-span of the slabs, and Case B was composed of: five slabs with no openings. For Case A, the five slabs were divided into: a control two-way slab with an opening in the mid-span; which was not strengthened, three two-way slabs each with an opening in the mid- span; they were strengthened internally using extra reinforcing steel bars around the opening; which had different development length, and finally, a slab with a mid-span opening strengthened with Externally Bonded Carbon Fiber reinforcing polymer (EB-CFRP) laminates at the tension side. Whereas, (Case B's) five slabs were: a square control slab, it was examined till failure to evaluate the slabs' capacity, and four two-way squared reinforced concrete slabs with no openings, they were tested following a certain sequence. It was as follows; the four two-way squared reinforced concrete slabs were loaded till the initial cracking load as that of the control slab. Then, the strengthening was installed, and the opening was cut at the mid-span. The loading continued till failure occurred. The strengthening was carried out using Near Surface Mounted technique (NSM) and EB CFRP. Test results showed that adding additional internal steel reinforcement around the opening caused a significant increase in the load carrying capacity of slabs. Using NSM technique, the technique proved to be efficient in restoring slab's load carrying capacity with increasing the length of the strengthening bars. Although the different codes did not mention any recommendations about creating the opening on the existing two-way RC beamed slab; it is suggested to use yield line theory as the reduction of the ultimate loads of the two-way beamed slabs due to creating openings and additional load due to adding strengthening reinforcing bars around the opening can be successfully calculated.

Mahmoud Elsayed et al. [16], conducted a numerical analysis of strengthening R.C slabs with opening using ferrocement laminates to investigate structural behavior of reinforced concrete slab with a centered square opening strengthened with ferrocement laminates. The 3-dimensional feature available in the commercial analysis package ANSYS was used to model the specimens. The model accommodates the material nonlinearities cracking and crushing of concrete and yielding of steel. Verification of study was calibrated with strengthened and unstrengthened numerical model by available experimental data. The studied parameters were; thickness of ferrocement layer, percentage of expanded wire mesh reinforcement in the ferrocement cover layer, compressive strength of mortar. Based on the results and observations of the numerical investigations presented in the study regarding the effectiveness of ferrocement laminates in strengthening slab with opening, it can be seen that ferrocement laminates can be successfully used for increasing the ultimate carrying capacity, strength, and energy absorption. The results showed that use of ferrocement enable the slabs to restore its full load capacity and increased its ultimate load carrying capacity up to 2 times.

Mahmoud Elsayed et al. [17], presented an experimental and numerical study to evaluate the effectiveness and feasibility of using ferrocement as external overlays for strengthening R.C. slab with a central opening. Twelve R.C slabs of dimension 1000 x 800 x 100 mm were cast and tested experimentally, ten of the specimens were strengthened by ferrocement laminates and the other two were kept as control specimens; with and without opening. The effects of mortar thickness, number, and type of steel wire mesh, ferrocement mortar strength, and strengthening schemes were investigated. A 3-D finite element model using ANSYS package was developed and compared with the available experimental test results to check the validity of the model. A total of 32 numerical models were analyzed to study the different parameters that not covered by the experimental investigation. This study provides information on the viability of using ferrocement laminates in strengthening R.C. slab with cut-out and showed that both flexural behavior and stiffness were significantly enhanced. It was observed that the influence of the openings is vanished by strengthening the test specimens by ferrocement. The ultimate load capacities of the strengthened specimens were increased between 186% and 80% relative to the control specimens with and without opening respectively. The finite element analysis was capable of reasonably estimate the experimental behavior.

Amirhossein Eskandarinadaf et al. [16], tested six full-scale two-way RC slabs with a central opening, in addition to one reference slab without opening until failure under monotonic and cyclic loading. These six slabs consisted of one control un-strengthened slab and five strengthened slabs. The strengthening methods used in this study were either Externally Bonded Glass Fiber Reinforced Polymer (EB-GFRP) or embedded extra steel bars at the tension side of the slabs, as proposed by ACI [17]. The test results show that using GFRP strengthening method could increase the ultimate strength and flexural stiffness of the slabs significantly. Moreover, embedding extra steel bars around the opening may not enhance the load-carrying capacity of the slab to the value of the continuous slab. The test results also show that the deflections of the strengthened slabs with opening under service loads are more than that of the slab without opening.

Syafiqah Shahrul Aman et al. [18], tested ten slabs to investigate structural behavior of slabs with openings coated with Carbon Fiber Reinforced Polymer (CFRP) sheet. The tested slabs were casted with a dimension of 1000 mm×530 mm×25 mm, among which nine slabs had openings and one slab was without opening (control slab). The configuration of the CFRP sheet includes coating in the form of single, double, and triple layers. Experimental results show that the slab with a triple coating of the CFRP layer offers the maximum resistance towards the loading rate. Moreover, with the increase in CFRP layers, the value of deflection is minimized.

Sameer Kumar et al. [19], worked on an experimental study to investigate the efficiency of Near surface mounting (NSM) technique using CFRP laminates in restoring the capacity of hollow core slabs with openings. Ten full scale hollow core slabs were tested under four-point loading at two shear span to depth (a/d) ratios and with two different locations of opening. All the slabs were 150 mm deep, 1200 mm wide, 3500 mm long and prestressed with six 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 behavior under different bending moment to shear force ratios. 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 x 600 mm (25% of the width of the slab) which was provided. The opening could be at the mid span location (Flexural Opening) or in shear dominated zone (Shear Opening). The size of the openings was chosen based on the discussions with local slab manufacturers and standard industry practices during casting. All the specimens with openings were strengthened with the four numbers of CFRP strips. The strips were 1.4 mm thick and 25 mm wide. Figure 10 shows cross section and plan view of slab with strengthening.

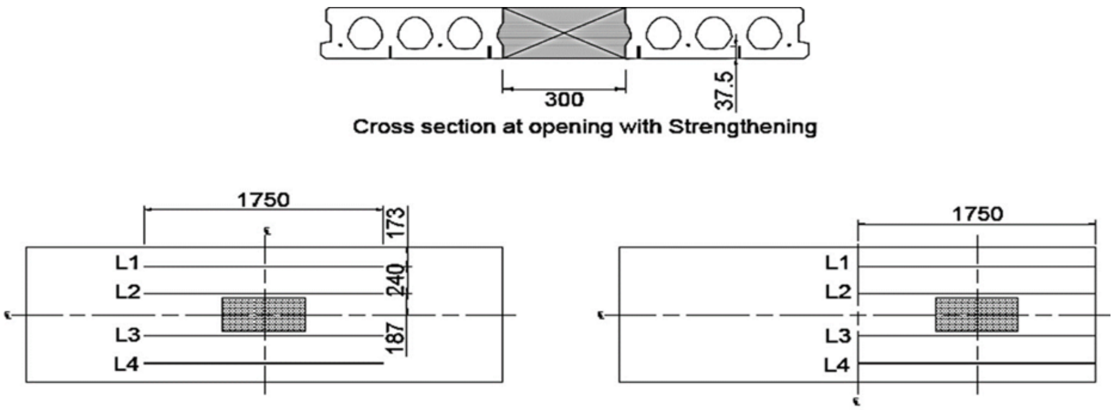


Figure 10: Cross section and plan view of slab with strengthening (All dimensions in mm)

The final results showed that 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. strengthening of slabs with both flexural opening and shear opening using CFRP strips by NSM technique has restored the full capacity of slab in all the cases except one. Opening in the slabs changed the mode of failure. In slabs with low (a/d) ratio, flexural opening converted the brittle shear failure to a ductile flexural failure. Strengthening of slabs with openings by CFRP strips has caused all the slabs to fail in shear, leading to decrease in ultimate displacement. In slabs with high (a/d) ratio, presence of shear opening converted the ductile flexural failure into a more brittle shear dominated one. Strengthening of slab with flexural opening has changed the ductile failure mode to brittle shear mode. And finally, CFRP strengthening of the slabs was very effective in restoring the loss in stiffness in slab with shear opening but did not restore in slab with a flexural opening.

Karam Mahmoud et al. [20], Tested five prestressed hollow-core slabs under four-point loading to failure. The slabs were 5000 mm long and 203 mm thick with a concrete cross-sectional area of 140,194 mm^2. The slabs originally had an internal prestressing steel reinforcement ratio of 0.00274. The prestressing reinforcement consisted of seven size 9 strands. In two of the slabs, an opening was cut within the flexural span to reduce the compression area and interrupt a pretensioned strand, which was expected to reduce the flexural capacity by a not-yet-determined amount. In addition, in two other slabs, an opening was cut in the shear span to reduce the web width and to interrupt the middle strand, which could adversely affect the shear capacity of the slab and possibly change the mode of failure. The fifth slab had no opening to serve as a reference. For each opening location, one slab was strengthened with the near-surface-mounted technique. The opening had a rectangular shape measuring 308 mm wide × 600 mm long, 0.25b × 0.5b, where b is the width of the hollow-core slab element and slabs details are shown in Fig. 11.

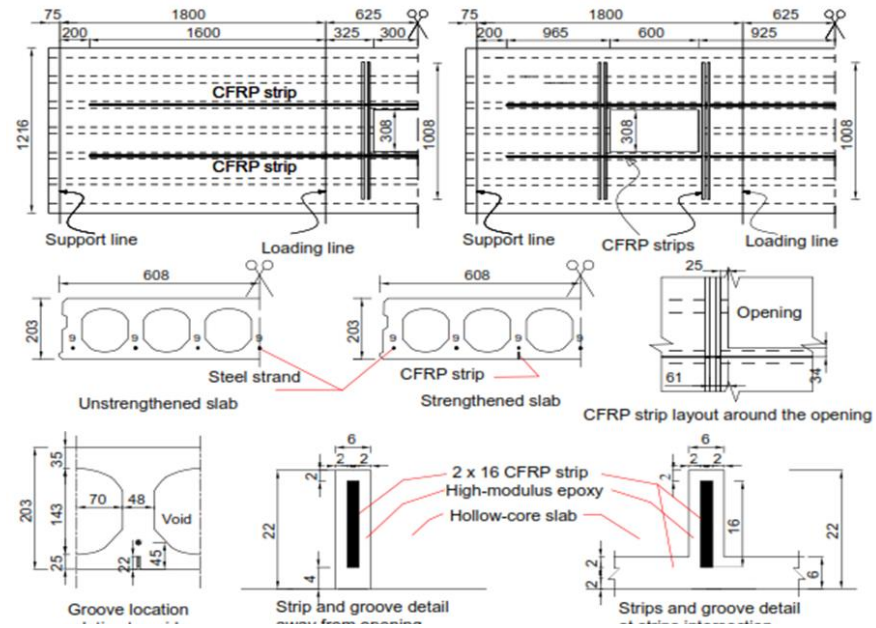
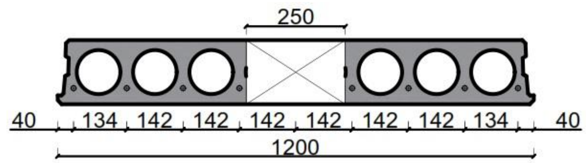


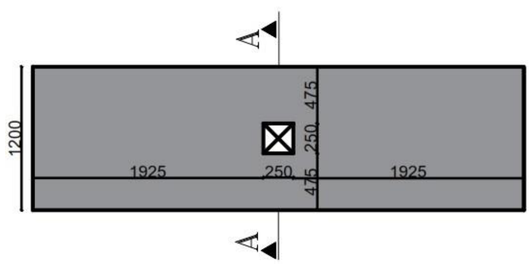
Figure 11: Details and cross section of test slabs and groove details near the voids

The findings of this investigation showed that the presence of an opening in the flexural zone of prestressed hollow-core slabs decreased the cracking, yielding, and ultimate moment, while adding an opening in the shear span had less effect on the overall performance of such slabs. Strengthening openings with two strips of near surface mounted CFRP not only restored the flexural Strength deficit incurred as a result of cutting the openings and the prestressing strand but provided additional flexural capacity. The post cracking stiffness of the slab decreased significantly (56%) with the addition of an opening in the constant moment region. Also, the addition of an opening in the shear span resulted in a 43% decrease in the post cracking stiffness. However, strengthening these openings with near-surface-mounted CFRP strips enhanced the post cracking stiffness, which increased 46% and 35% in specimens with flexural opening and shear opening, respectively, compared with their unstrengthened counterparts. Compared with the reference slab, slabs with openings exhibited higher deflection ductility and energy ductility, which could be attributed to reduced flexural stiffness after cutting the opening. Strengthened slabs showed higher ductility than their unstrengthened counterparts; however, this increase in ductility is attributed to the higher ultimate loads and the corresponding deflections of the strengthened slabs.

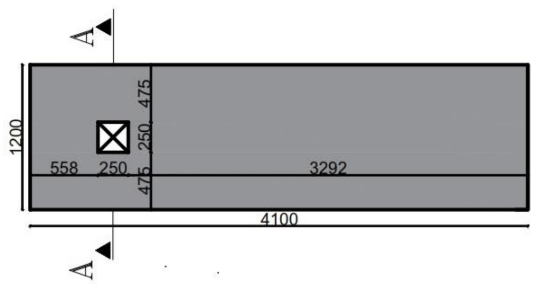
Ahmed Elkhouly et al. [21], Studied the effects of openings on flexural and shear behavior of precast prestressed hollow core slabs. Three full-scale hollow core slabs of dimensions 4100x1200x160 mm were tested in reinforced concrete laboratory at Menoufia University. One slab without opening is considered as a control specimen. The second slab (PPHCS2) with a central opening with dimensions 250x250 mm at mid of span was tested to investigate the effect of this opening on the flexure capacity. The third slab (PPHCS3) has an opening at mid of one-third of span was tested to investigate the effect of the opening on shear capacity of hollow core slab. The slabs contain 9 strands and to make the opening the middle strand had to be cut. All specimens were tested under four loading points until failure. In the second and third specimens, to make the opening one strand (the mid strand) had to be cut. The cross section and openings locations for specimens are shown in Fig. 12.



(a): Section A-A



(b): Flexural opening



(c): Shear opening

Figure 12: Openings locations for PPHCS2 and PPHCS3

The study was seeking to investigate the behavior and capacity of slabs with and without opening at mid-span and mid of one-third of specimen. Depend on investigational results; Making an opening at mid of span reduced the stiffness and decrease the flexure capacity of the slab. The first cracking load was decreased by about 23.50%, and the failure load was decreased by 11.40% with respect to control slabs results. The opening at mid span did not affect the failure mode as it remained ductile as control slabs specimen. For the opening at mid of one third of span (at max shear), as there is no steel to resist the shear (only concrete) the opening had a very bad effect on slab at this zone as the specimen failed suddenly. The first cracking load and failure load was decreased by about 6% and 21% respectively with respect to control slab.

Sameer K. S et al. [22], developed a three-dimensional FEMs and were calibrated with Six full-scale hollow-core slabs to predict the behavior of prestressed hollow-core slabs with openings. All of the tested slabs had the same cross-sectional details. Each slab was 150 mm deep, 1200 mm wide, and 3500 mm long. The slabs were prestressed with six 9.53 mm diameter prestressing strands with a prestressing jacking force of 70 kN. One 300 × 600 mm opening was provided, either at the midspan location (flexural opening) or at the shear span location (shear opening). Two strands were cut at the opening location. After the calibration of the developed FEMs, a parametric study was conducted to investigate the effects of opening size, a/d, and additional strands. The finite element analysis was conducted for limited parameters in this study.

Results of the finite element analysis indicate that the provision of openings reduced the strength and stiffness of the slabs, depending on the a/d. The reduction in strength and stiffness due to flexural opening was higher in higher (a/d) specimens, whereas the shear opening was found to be critical in specimens tested at a low a/d. Parametric results indicated that the opening size should be carefully selected based on the location of the opening. Increasing the opening size in a shear-dominated zone results in more adverse behavior than increasing the opening size at the midspan location. The common methodology of designing hollow-core slabs with openings, where the number of strands is increased by the number of strands cut, was found to be inconsistent in restoring the capacity of slabs with openings. A thorough case-by-case analysis of the slabs is required to evaluate the effects of openings.

5. CONCLUSIONS

The main conclusions can be summarized as follows:

- Opening size should be carefully selected based on the location of the opening. Increasing the opening size in a shear-dominated zone results in more adverse behavior than increasing the opening size at the midspan location.
- For the opening at max shear, as there is no steel to resist the shear (only concrete) the opening had a very severe effect on slab at this zone as the specimen had a brittle failure.
- Considerations should be given while calculating the sectional capacity of slabs based on the loading conditions. It was observed that shear-dominated loading can significantly decrease the sectional capacity of hollow-core slabs both with and without openings.
- Slabs with flexural openings exhibited higher deflection ductility and energy ductility, which could be attributed to reduced flexural stiffness after cutting the opening.
- Strengthening openings with near surface-mounted is an effective strengthening method and is applicable to restore the flexural strength deficit incurred due to cutting the openings and the prestressing strand and provide additional flexural capacity.

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