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Prestressed Precast Hollow-Core Slabs with Different Shear Span to Effective Depth Ratio

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Abstract. Four full scale precast prestressed hollow-core slabs were tested under the influence of four lines loading with various values of shear span to effective depth ratio (a/d) (1.5, 2, 3.5 and 5). The dimensions of the hollow-core slab were 2000 mm, 1200 mm and 150 mm (length, width and thickness, respectively). All slabs were cast with a high compressive strength concrete of approximately 79.5 MPa. Experimental test results showed four patterns of failure mode depending on the ratio of (a/d). They were flexural failure, flexure-shear failure and shear compression failure. In addition to combination failure between tension shear and anchorage failure, accompanied by sliding strand in concrete. The failure loads decreased about 19.6% as (a/d) increased by 233.3%. Finally, the highest first crack load, 110kN, was recorded for sample, HCS 1.5, having the lowest (a/d) ratio.

Keywords: *Precast, prestress, hollow core slabs, shear span to depth ratio* .

البلاطات المجوفة مسبقة الصب والجهد مع نسب مختلفة لفضاء القص الى العمق الفعال

الخلاصة. يتكون برنامج الاختبار التجريبي من أربع بلاطات مجوفة مسبقة الجهد والصب ، اختبرت تحت تأثير أربع خطوط تحميل ، مع قيم مختلفة لنسبة فضاء القص الى العمق الفعال (a / d) حيث كانت (1.5 ، 2 ، 3.5 و 5). كانت ابعاد البلاطة المجوفة المسبقة الجهد 2000 ملم، 1200 ملم و 150 ملم (الطول ، العرض والسمك، على التوالي) . جميع البلاطات صبت بخرسانه ذات مقاومة انضغاط عالية بحدود 79.5 ميجا باسكال. أظهرت نتائج الاختبار التجريبي أربعة أنماط من الفشل تبعاً لتنوع قيم نسب (a / d) ، وهي فشل الانثناء، فشل الانثناء - القص ، وفشل ضغط القص بالإضافة إلى فشل جمع بين فشل قص الشد والتثبيت يرافقه انزلاق حديد التسليح في الخرسانة . انخفضت أحمال الفشل بنسبة 19.6٪ عندما ارتفعت نسبة (a / d) الى 233.3٪. وأخيرا، تم تسجيل أعلى حمولة للتشقق الأولى، 110 كيلو نيوتن ، للعينة HCS1.5، ذات أدنى نسبة (a / d) .

1. Introduction

Hollow core slab (HCS) structural system was first introduced in 1950 when the technology of pre-stress entered the mass product phase [1]. HCS was characterized as a high quality in the production point of view due to high quality control, great reduction in the self-weight and the lower production costs. Therefore, its production spread on a large scale worldwide [2-4].

HCS is usually produced with high-strength concrete, and reinforced by using high strength prestressing strands of diameters between 9 and 13 mm as reinforcement. The strands are sleeved in holes extended along the longitudinal axis of the slab to reduce the slab self-weight, and to improve several properties such as voice and thermal isolation and fire resistance. The HCSs are often produced with thickness of 100 to 400 mm, and width of 900 to 1250 mm. The length of the span can be as long as 18 meters. The HCS is always designed as simply supported panel. The production technique of HCS does not allow possible establishment of shear and torsion reinforcement. Therefore, it may fail without warning due to shear and/or torsion stresses [5].

Recently, Experimental studies were intensively conducted to improve the performance of HCS by using of steel fiber, vinylon fiber, polyethylene fiber and carbon fiber. Carbon Fiber Strips (CFS) are usually used in strengthening of HCS to increase their flexural strength [4,6-9] . Six specimens were strengthened with CFS and subjected continuously to a negative moment until failure. The results showed an improvement in the resistance of negative moment up to 574% compared with control samples tested without strengthening [6].

Twenty six HCS specimens of thickness of 260mm and compressive strength of 70 MPa were tested under a four-point load. They were reinforced with different ratios of steel fibers ranged 50 to 70 kg/m3. The test results confirmed that the use of steel fibers is a good solution to overcome the shear failure as they improved the shear capacity and gave greater margins of safety (20 - 30%), with significant enhancement in ductility [10]. Other studies [4, 8 ,11- 12] used 48 kg of steel fibers per cubic meter of concrete. The test programs included different ratios of (a/d). Physical observation showed a delay in the occurrence of cracks in addition to the improvement of many mechanical properties such as plasticity, hardness and control over the types of failures.

A total of 15 samples of HCS had various thickness from 200 to 300 mm ,were subjected to a four-point load to study the effect of thickness on failure mode. The study results indicated that the failure would change from flexure to the flexure-shear failure when the thickness of the slab was increased. Moreover, the shear strength decreased with the increasing of the thickness of HCS [13]. Other researchers [14, 15] investigated the effect of the surface condition of HCS topped with 50 mm of plain concrete. The study included 24 samples with dry and wet surfaces roughening. The results of the study showed significant improvement in the cracking moment, initial stiffness and ultimate moment capacity by 22, 93 and 23%, respectively. Moreover, the shear strength and the horizontal slip capacity were enhanced considerably, when the groove was perpendicular to the applied shear.

The production of HCS is done by the extrusion only. This production method does not allow placing the shear reinforcement. Besides, the thickness of the slabs is limited. Accordingly, there is a great possibility for shear failure under loading. This paper aims to understand the effects of shear span to effective depth ration on the structural response of hollow-core slabs subjected to four-bending test.

2. Experimental Program

2.1. Material Properties

The experimental program consisted of testing four full-scale precast prestressed hollow-core slabs. They were fabricated by AL-borhan factory for precast concrete in Kut city. All samples were designed in accordance to the provisions of the British Code BS 8110-1 (1997) [16].

The concrete mix in all HCS samples was designed to give zero slump, the mix material included; Ordinary Portland cement, 6–12 mm gauged coarse aggregates, and the fine aggregates with two grades: 0–6 mm and 0–4 mm. The water cement ratio was kept constant for all slabs mix, which was 0.3.

Twelve 150 mm-side length standard cubes were cast during the fabricating of HCS slabs to measure the compressive strength of concrete at ages of 7 and 28 days. The reinforcement of samples was composed of seven-wires 9.3 mm diameter low-relaxation strands. The concrete cover was 30mm from top and bottom. The specimens were cast in continuous bed by an extrusion machine. The concrete was cured by using the heating system and early continuous covering, for eight hours. The hammer test was used to predict the initial compressive strength of the concrete, which are about 21-25 MPa , when the compressive strength of the concrete reached these values, the samples were cut to the demanded length. Fig. (1) illustrates the extrusion, the curing of the concrete and the cutting of the hollow core slabs processes.

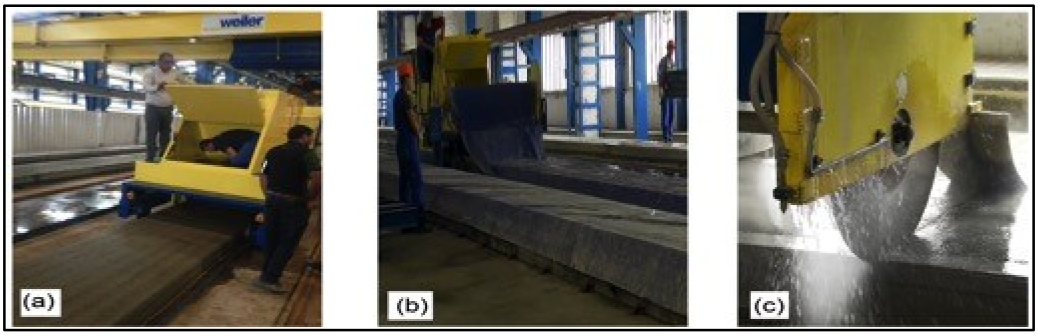

Figure. 1. (a) Extrusion process. (b) curing of the (HCS) .(c) cutting of the (HCS)

All the tested specimens had the same dimensions, 2000 mm long, 1200 mm wide and the 150 mm thick. Fig. (2) shows the typical cross-section of the slab specimens and Table (1) summarizes the details of the used materials in the concrete mix and the specifications of the prestress strands.

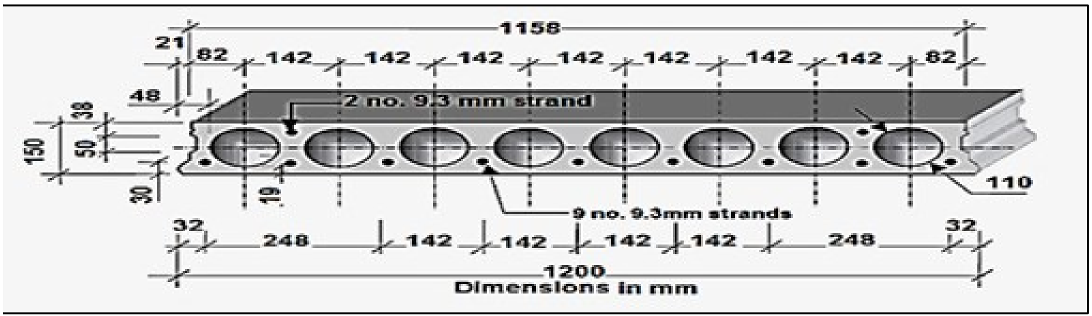

Figure. 2. Details of the 150 mm precast-prestressed hollow core slabs adopted in the experimental investigation .

Table (1) Mix design and mechanical properties of concrete and prestrss strands

Concrete		Prestressing strands	
Mechanical properties	Values	Mechanical properties	Values
Compressive strength (7 days)	54 MPa	Diameter	9.3 mm
Compressive strength (28 days)	97.4 MPa	Nominal cross sectional area	51 mm^2
Max water-cement ratio	0.3	Ultimate load	94 KN
Cement content	390 kg/m^3	Ultimate tensile strength	1760 MPa
coarse aggregate (6-12)mm	1110 kg/m^3	Modulus of elasticity	198 GPa
fine aggregate (0-6)mm	275 kg/m^3	Max elongation	3.5 %
fine aggregate (0-4)mm	500 kg/m^3	Initial prestressing strain	0.556 %
Precast slab weight	2.04 kN/m		
Area of section	0.0102 m^2		

2.2. Test Setup And Loading Details

In the test program, one parameter was varied which was the shear span-to-effective depth ratio (a/d). The values of (a/d) were 1.5, 2, 3.5 and 5, based on which the precast prestressed hollow-core slabs were coded as follows HCS 1.5, HCS 2, HCS 3.5 and HCS 5, respectively . The HCS slabs were tested under four loading-lines with clear span of 1800 mm. The load application was through increments of 10 kN till failure of samples. In each load increment, the deflection of samples was observed by using dial gauges placed in the bottom of samples at three locations; center of samples and under points of applied loads. In addition, the cracks configuration and propagation were carefully investigated. . Fig. (3) shows all the details of the test setup .

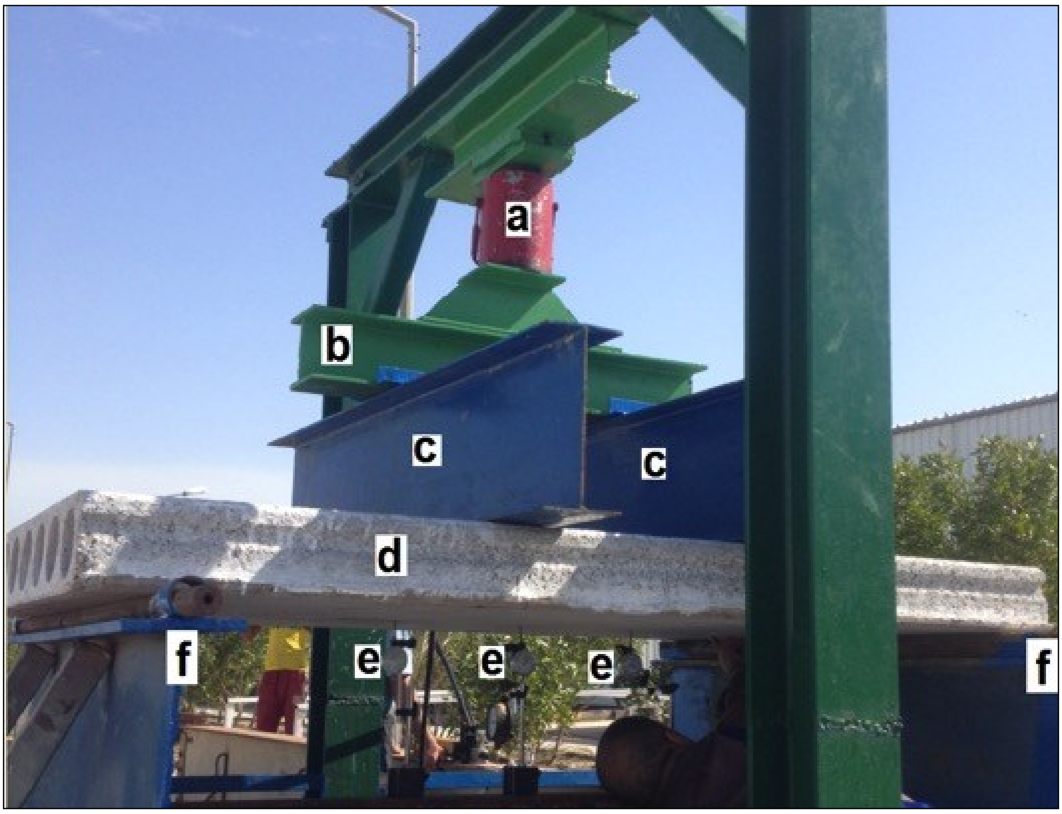

Figure. 3. Specimen cross section, instrumentation and loading setup details
(a) hydraulic jack. (b) spreader beam. (c) Transverse I-beams. (d) hollow core slab. (e) dial gauges . (f) support I-beams.

3. Tests Results And Analysis

3.1. Cracking And Failure Loads

The specimen were tested under loading which was increased gradually until failure. For HCS5, the initial flexural crack appeared at 42 kN, which is about 36% of the ultimate load capacity. This crack initiated at the constant moment region (mid-span). As the applied load increased, the flexural cracks increased also, and propagated toward the compression zone as well as became wider. An initiation of new flexural cracks were observed at a location bonded between line of applied loads and supports line. Then, these cracks propagated inclined toward the loading lines at applied load of 70 kN. Finally, the HCS 5 failed in flexure at an ultimate load of 115 kN.

The behavior of the HCS3.5 was similar to that of HCS5 during the early stages of loading. It exhibited the first crack at load of 55 kN. However, with the increasing load, the flexural cracks in the shear span evolved faster than did the flexural cracks between the line loads. Then, they became inclined and extended towards the loading lines. At load of 120 kN, this sample failed in flexure-shear failure with crack angle of approximately 19º.

In HCS2, cracks first appeared when the applied load reached 70 kN at shear span region near supports, which is about 52% of the ultimate load capacity. As the load increased, these cracks propagated towards the support lines. At an ultimate load of 135 kN, the slab failed rapidly with a crack angle of approximately 28º.

The HCS1.5 showed different behaviors from previous slabs because the slab dissipated its energy at the initial stages. For this reason, flexural cracks or flexural shear cracks did not appear at this stage. When the applied load reached 110 kN, about 78% of the ultimate load capacity, the first diagonal crack appeared near the support. At higher loads, the first crack expanded increasingly toward the line load with the appearance of another crack from the other side at the same support. This was accompanied with the appearance of a crack parallel to the longitudinal axis of the slab passing the line load towards the support. The HCS 1.5 showed a sudden failure with a combination between tension shear and anchorage failure at an ultimate load of 143 kN . The angle of the crack was nearly 44º. Table (2) shows the experimental test results for the tested slabs. Fig. 4. shows the failure crack pattern at the tension surface of the tested HCS slabs.

Table (2) experimental test results

Slab ID	a/d	Cracking load (Pcr) kN	Load at (Pu) Failure kN	% (Pcr) / Pu	Failure mode
HCS 1.5	1.5	110	143	77.92	tension shear and anchora failure
HCS 2	2	70	135	51.85	Shear compression Failure
HCS 3.5	3.5	55	120	45.84	Flexural shear Failure
HCS 5	5	42	115	36.52	Flexural failure

Figure 4. Cracks pattern at the tension surface of the four specimens.

3.2. Load – Deflection Relationship

Fig . (5) shows the relationship between the applied load and the deflection at mid- span for the four slabs. It can be seen that the responses of all slabs were similar during the early stages of loading. Then after, the deflections increased with increasing the applied load. At same load, the specimens of higher (a/d) ratio exhibited more deflection than did those of smaller (a/d) ratio. This is because the moment increases with augmenting (a/d) ratio. Furthermore, the plastic plateau was showed clearly in the load deflection curves of specimens HC3.5 and HC5, indicating a ductile failure for these specimens.

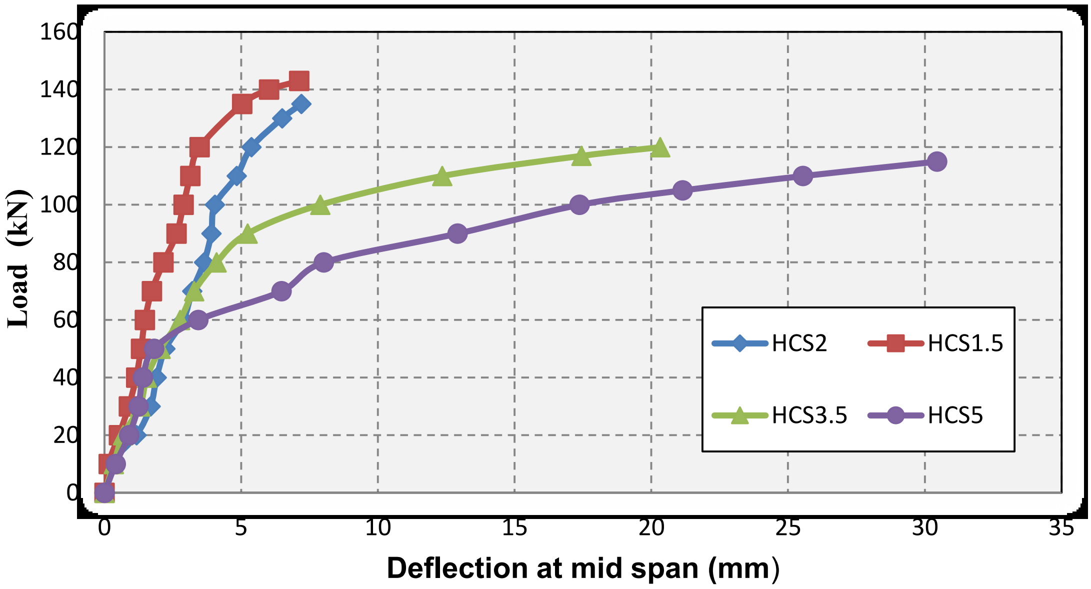

Figure. 5. Load–deflection response

3.3. Shear Span to Effective Depth Ratio and the Angle of the Cracks

Fig . (6) illustrates the relationship between the load capacity and the shear span to effective depth ratio. It is obvious that the failure load increases with decreasing the shear span to effective depth ratio. The failure load was increased about 24.3%, 17.4%, and 4.3% as the shear span to depth ratio decreased about 70%, 60%, and 30%, respectively.

Fig . (7) shows the relation between the crack angle which was measured between the crack failure and the horizontal axis of the sample and the shear span to depth ratio. It is clear that the crack angle decreases significantly at low values of (a/d). On the other hand, for high values of (a/d) , the decreasing rate of the crack angle was much slower.

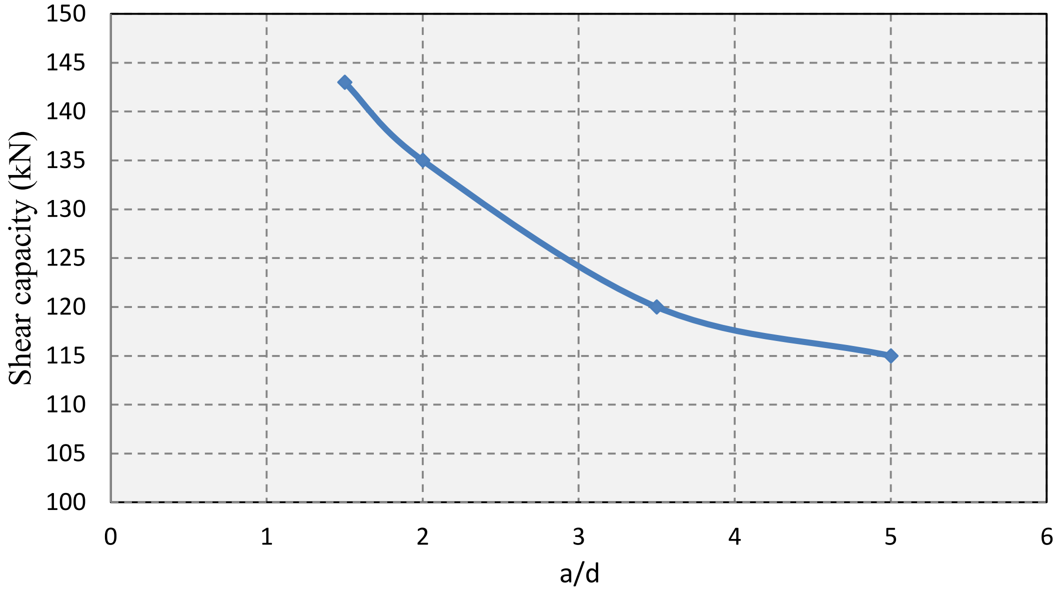

Figure. 6 . Relation between shear force and shear span to depth ratio.

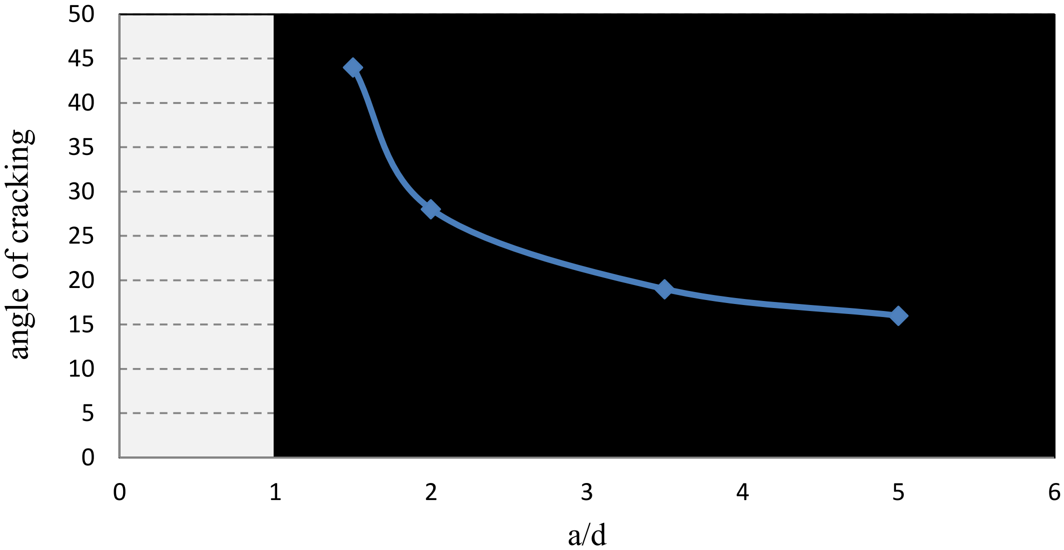

Figure. 7. Relation between the crack angle and shear span to depth ratio.

3.4. Failure Modes

Different modes of failure were observed and it can be postulated that their occurrence was according to the value of shear span to effective depth ratio, which is the main parameter of this study. All different modes are shown in Fig. (8) and they are as following: -

- Flexural failure

This type of failure occurs when the tensile stress exceeds the tensile strength. The flexural failure starts with vertical cracks which reduce the depth of the compression zone. Steel area in HCS is often small.

Therefore, this type of failure is characterized somewhat with high ductility. This can be clearly noticed in HCS5 , as shown in Fig**.** (8-A).

- Flexural shear failure

The flexural shear failure is initiated by the development of flexural cracks formed in the shear span during the early stages of loading. Then after and as load increases, these cracks propagate through the diagonal direction toward the line load, which leads to flexure shear failure, as shown in Fig**.** (8- B) for HCS3.5.

- Shear compression failure

After the flexural crack is developed to shear crack under the influence of the increasing load, this type of failure occurs. The prestressing force, reinforcement ratio and concrete strength are the primary factors that control the delay of the occurrence of this type of failure and the reduction in the crack width . This failure occurred in the case of HCS2, in which the value of the shear span to effective depth ratio was low as shown in Fig**.** (8-C).

- Tension shear and anchorage failure

Tension shear failure takes place when tensile stresses reach their critical values under the effect of the vertical pressure resulting from the support. In this region, this effect is also accompanied with the prestressing force, which is distributed regularly on the cross-section. Whereas, in the internal region, the stress is due to the prestressing force, in addition to the applied load. This makes the intense distribution of high stresses through the web of the slab between the holes. The low strength of the HCS1.5 in a plane inclined at 44º from the internal border of the support and the length of the anchored strand was not a sufficient anchorage. This resulted in an anchorage failure with large rotations. Shear tension and anchorage failure were corresponded when (a/d) ratio was 1.5, as shown in Fig. (8-D) and (8-E).

- Sliding of the strands in concrete

When the crack is formed near the support, all the forces are transferred to the uncracked zone. As a result, the strands would slip whenever the length of the portion extending from the support to the edge of the slab is very short. This would cause an increase in the crack width. The strands consist of a central wire surrounded by the rest, thus frictional stress is generated. If the frictional stress is large enough to get equilibrium, the strands would stop slipping. This failure occurred in the case of HCS1.5 as shown in Fig**.** (8- F).

Figure. 8. Crack pattern and Failure modes of slabs .

(A) Flexure failure mode of (HCS5), (B) Flexure- shear failure mode of (HCS3.5), (C) Shear compression failure mode of (HCS2), (D) Combination of tension shear and anchorage failure of (HCS1.5), (E) Crack . caused by tension shear and anchorage failure simultaneously , (F) Sliding of the strands in concrete

4. Conclusions

In this study, an experimental work of four full scale,precast and prestressed hollow core slabs was reported to investigate the behavior and the failure modes of such kind of slabs considering the shear span to effective depth ratio (a/d) as the main parameter. The prominent results of the experimental tests can be summarized as follows:

- ❖ The failure mode was varied depending on a/d ratio. The pure flexural failure occurred when (a/d) equals 5 at ultimate load of 115 kN with a crack angle of about 16º. At (a/d) of 3.5, the peak load was

120 kN and the failure mode was flexure shear failure with a crack angle of approximately 19º. When (a/d) equals 2, the ultimate load was 135 kN, the failure mode is shear compression and the crack angle was nearly 28º. Diagonal tension and anchorage failures were coincided when (a/d) equals 1.5 and they accompanied by the sliding of the strand in concrete. This failure mode was sudden at an ultimate load of 143 kN and a crack angle of approximately 44º.

- ❖ The specimens with low ratio of a/d were stiffer than those of larger a/d ratio.
- ❖ The failure load of specimens increased about 24.3% as (a/d) ratio decreased about 70%.

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