ANALYSIS OF COMPOSITE ACTION OF PRECAST HOLLOW CORE SLABS AND CAST IN PLACE MESH REINFORCED CONCRETE TOPPING

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by

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Abstract

Considering composite action of hollow core slab with cast in place mesh reinforced concrete topping helps to provide longer hollow core slabs and reduces the overall weight of the structure. Research has shown that composite action normally can be attained through studs or other connecting elements from the bottom element but for hollow core slabs the roughness of the top surface is enough to attain the composite action. This study aims to analyze the composite action of hollow core slabs made of ELEMATIC sections with thicknesses 150mm and 265mm with cast in place mesh reinforced topping. The thickness of topping was considered as 65mm for 150mm thick hollow core slab and 70mm for 265mm thick hollow core slabs.

A load test setup was made for both 150mm thick hollow core slab and 265mm thick hollow core slab which mirrored the actual site condition. The connecting reinforcements were provided as per normal practice and the supports were considered as simply supported after which the topping was setup with the wire mesh and the concrete poured. Readings from the three gauges below the hollow core slabs were recorded at 0% loading, 25% loading, 50% loading, 75% loading, 100% loading, 100% sustained loading and 0% released load condition after 24 hours. For 150mm thick hollow core slabs, 0.29mm was the deflection for 100% sustained loading and for 265mm thick hollow core slabs, 3.36mm was the deflection for 100% sustained loading. These two values are way less than the actual estimated values. The results indicate that composite actions are valid for uncracked hollow core slab sections considered in the tests. Further investigations can confirm the composite action for other hollow core slab sections and also for section which are cracked.

ملخص ألبحث

تعالج هذه الدراسة العقدات المجوفة والتفعيل المركب مع طبقة الخرسانة المسلحةلتحسين أداء هذه العقدات مع مسافات أطول للعقدات المجوفة مع تقليل في الاوزان لمنظومة القدات. لقد أظهرت ألدراسات تفعيل العمل المركب في العدات باستعمال مسامير او روابط اخرى. لكن مع العقدات المجوفة يعتبر الخشونة في السطح العلوي للعقدات المجوفة كاف لتشغيل الفعل المركب. في هذه الدراسة سنقوم بتحليل الفعل المركب لعقدات مجوفة بتجويف قطره 150 ملم وسماكة 265 ملم مع طبقة خرسانة علوية مسلحة بشبكة حديد, سماكة هذه الطبقة 65 ملم لعقدات بتجويف 150 ملم و 70 ملم لعقدات بتجويف 265 ملم.تم إجراء عدد من اختبارات الحمل على كل من اللوح الأساسي المجوف بسمك 150 مم والبلاطة الأساسية المجوفة بسمك 265 مم والتي تعكس حالة الموقع الفعلية. تم توفير تعزيزات الحسور الحاملة وفقًا للممارسة المعتادة واعتبرت الجسور مساندة ببساطة وبعد ذلك تم وضع الطبقة العلوية مع شبكة سلكية وسكب الخرسانة. تم تسجيل قراءات من المقاييس الثلاثة الموجودة أسفل الألواح الجوفاء عند التحميل بنسبة٪ 0 ، التحميل بنسبة٪ 25 ، التحميل بنسبة٪ 50 ، التحميل بنسبة٪ 75 ، التحميل بنسبة٪ 100 ، التحميل المستمر بنسبة٪ 100 ، حالة التحميل التي تم إصدارها بنسبة 0٪ بعد 24 ساعة. بالنسبة للألواح الأساسية المجوفة بسماكة 150 مم ، كان انحراف 0.29 مم للتحميل المستمر بنسبة 100٪ وللألواح الأساسية المجوفة السميكة بقطر 265 مم ، كان 3.36 مم هو الانحراف للتحميل المستمر بنسبة 100٪. هاتان القيمتان أقل من القيم الفعلية المقدرة. تشير النتائج إلى أن الإجراءات المركبة صالحة لأقسام العقدات الجوفاء غير متشققة تم أخذها في الاعتبار في الاختبارات. يمكن أن تؤكد الفحوصات الإضافية الإجراء المركب لأقسام البلاطات الأساسية الأخرى المجوفة وأيضًا بالنسبة للقسم المتشقق

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Sajjad Omer

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Symbols and Abbreviations

ACI	American Concrete Institute
A142	6mm diameter wire mesh with a spacing of 200mm c/c both vertically and horizontally
c/c	center to center
D	Design Floor SDL
dia	diameter
f’c	Characteristic concrete compressive strength (Cube)
fy	yield strength
HCS-150	Hollow core slab with 150mm thickness
HCS-200	Hollow core slab with 200mm thickness
Kg	Kilo gram
Kg/m^2	Kilo gram per m^2
KN	Kilo Newton
KN/m^2	Kilo Newton per m^2
KPa	Kilo Pascal
L	Design Floor Live Load
Lr	Roof Live Load
MPa	Mega Pascal
m	meter
mm	millimeter
N	Newton
R	Rain Load
S	Snow Load
SDL	Superimposed dead load

CHAPTER 1: Introduction

1.1 Introduction

Construction industry has developed and matured over time. In the modern construction techniques reinforced concrete has gained prominence over other types of construction due to its flexibility and fire resistance capabilities. Precast concrete elements are also a part of reinforced concrete system. Precast concrete elements are the parts of a building or bridge or any construction element which are manufactured in factory and erected at site. A whole building or a tower or a bridge can be separated into smaller segments and assembled at the construction site with the help of cranes. Since the elements are manufactured in a controlled environment, precast concrete components are superior in their quality when compared to their cast in place counterparts. Precast concrete has been an indispensable part of modern construction industry due to the speed of erection and quality provided. In places like China precast concrete has found more favor than the traditional cast in place construction in the recent times since it reduces the rubbles during erection. Since the introduction it has been observed that there is a significant improvement in air quality. Since the precast concrete elements are produced in the factory difficult architectural features are conceived through expert craftsmen, engineers and architects. In case of large-scale typical construction like Villas precast concrete helps in minimizing the wastes, better man management and timely deliverance of the projects. Precast elements are also used as claddings to improve the aesthetic appearance of RCC and steel buildings. With the usage of insulation materials, precast wall panels are generally preferred to reduce heat and in turn reduce the power consumption.

1.1.1 Precast concrete in the United Arab Emirates

Precast concrete is an integral part of the dynamic construction market in the UAE because of its many advantages and speed being the major one. Apart from the thousands of villas which are made by precast concrete annually many of the keystone projects in the UAE have precast concrete components. Some of the projects include Mall of the Emirates car parking, Dalma Mall, Dubai Auto drome stadium, Dragon Mart carpark, Dubai airport tunnel, Etihad railways, IKEA in Yas

Island, Al Wahda Mall and so on to name a few. Many of the high-rise projects in the United Arab Emirates uses hollow core slabs as the slab system. Even though in most of high-rise buildings in the UAE precast components are not being used structurally, hollow core slabs are used widely as a structural slab system. In the projects such as Armada tower in Dubai and Nation towers in Abu Dhabi hollow core slabs have been extensively used.

1.1.2 Hollow core slabs as precast elements

Since hollow core slabs doesn't require special molds or number of workers as other precast elements, the manufacturing process is relatively brisk. As there is no need to make new molds and there are only typically 5 to 6 types of hollow core slabs with precast manufacturers, the price of the hollow core slabs is also comparatively cheap. The process of erection and transportation of the precast prestressed hollow core slabs are also rather uncomplicated because of their standard sizes. The presence of prestressing strands increases the pre camber in the slab due to which the effective deflection will be lesser in hollow core slab. These combined with other factors make hollow core slabs one of the most manufactured precast concrete part in the United Arab Emirates.

1.1.3 Importance of research in hollow core slabs in the UAE

Notwithstanding the sheer volume of hollow core slabs in the construction market in the UAE, the data available for major discussions within the industry regarding hollow core slab properties are rare. In this dissertation we will be discussing in particular the composite action of hollow core slabs with the structural screed. Unlike the prevalent pattern in the composite sections in which there will be some sort of connection with the main element and the topping like steel studs or reinforcements from the bottom slab, the composite action in hollow core slabs are chiefly realized through the roughness of the top most part of the hollow core slab. Upper part of the hollow core slabs is intentionally roughened almost entirely in the factory and rarely at the site.

Most of the hollow core slab projects in Abu Dhabi emirates consider the composite action but in Dubai emirates composite action is rarely considered which results in considerable increase in the cost of projects. This investigation on the composite action in hollow core slab sections is an attempt to verify the composite action simulating the actual connections and site conditions of the United Arab Emirates.

1.2 Research question

How do the composite action of hollow core slabs with topping correlate with the software analysis of the hollow core slabs with topping? Concrete topping when considered as a structural element along with the hollow core slabs helps remarkably with structural performance of the slab system. In some cases, during analysis stage toppings are not considered as a composite section along with the hollow core slabs to attain more conservative design. This has been the approach in many a project especially in Dubai.

1.3 Objective and scope

The objective of this research is to establish that the topping can be considered with hollow core slab as a single structural composite element for all practical purposes even without steel anchors. This is to be established through a test which resembles the actual site condition and comparing with the software analysis results. Hollow core slabs of 150mm and 265mm are only considered in this study. Displacements from the software analysis and the tests will be compared to check if the results are comparable. Since the test is non – destructive, the comparison between the software and actual system will be limited to the displacement limits only. Since this research tries to simulate the real site condition and the software which is widely used in analysis of hollow core slabs, Concise beam is used here, the research can be used as a reference for future and undergoing projects especially in the United Arab Emirates and the Persian Gulf region in general.

1.4 Structure overview

The study comprises of 6 chapters. Introduction forms the 1st chapter, 2nd chapter the literature review, 3rd being the research methodology followed by test results and discussions as the 4th chapter, software analysis of the composite and non-composite structures covers the 5th chapter and the conclusion makes up the final or 6th chapter.

2nd chapter reviews the previously available resources on the composite elements. Firstly, composite action on materials other than concrete due to the concrete topping will be discussed. Then the composite action of concrete topping with concrete elements other than hollow core slabs will be examined moving on to which hollow core slabs without topping will be reviewed and finally literatures of hollow core slab with cast in place topping will be deliberated.

3rd chapter examines the research methodology in which the load setup will be primarily discussed. Material properties of the hollow core slabs and the structural toppings will be looked upon here following which the acceptance criteria based on ACI 318M-11 section 20.4 and 20.5 will be discoursed about. Loading sequence and the result inspection method will also be conversed later on.

4th chapter is about the test results and its discussions. Results will be tabulated and graphs will be generated accordingly. Results for all the hollow core slab thickness will be reviewed and compared in this chapter.

In the 5th chapter the software analysis is done and verified with the results. All the relevant graphs such as the moment diagram, shear diagram, deflection diagrams, stressing patterns will be looked upon here. A detailed report for each case will also be generated. In the 6th and the final chapter it will be concluded how the analysis results of the composite and non-composite elements can be compared with the actual test results.

Chapter 2
Literature Review

2.1.Introduction

Precast Concrete has been widely popular in recent years. A main component in precast concrete structures is the Slabs.

There are different types of precast concrete slabs used,

- Precast non-prestressed solid slab
- Precast prestressed solid slabs
- Precast prestressed Hollow Core slabs
- Precast prestressed double tee slabs

Many a company uses their own proprietary precast slab systems also. But the most commonly used precast slab system is the hollow core slabs.

Hollow core slabs are mainly designed as one-way slabs with structural screed of varying thickness of 50 to 100 used as per the requirements. The main purpose of the structural screed being the proper distribution of the loads over hollow core slabs and to transfer the lateral loads like wind loads and seismic loads to the beams and then to the vertical elements.

Moreover, the structural screed significantly increases the structural properties like flexural and shear capacity of the slab system in the building. For attaining the composite action between the hollow core slabs and topping the top of hollow core slab in intentionally roughened during manufacture. We will be using Concise beam software to the check the structural characteristics of the hollow core slabs. To verify the structural properties of composite characteristics of the hollow core slab with the calculated ones we will be conducting load tests on the hollow core slabs as specified by ACI recommendations. In this research, we will be checking the deflection of the hollow core slabs before and after loading.

In order to attain the goal of this research it is crucial to examine previous researches in hollow core slabs. To attain shear friction between hollow core slab and topping, according to ACI 318 M-08, 11.6.9, before the pouring of topping, the surface of the hollow core slab shall be clean and free of fine particles above the concrete. The surface of the concrete should be roughened to 6mm approximate amplitude. There is no special requirement of reinforcing steel to be produced from the hollow core slabs. Most of the manufacturers use intentional roughening of the hollow core slab surface when it used as building slab. Smooth surfaces are preferred for hollow core slabs used as boundary wall elements.

The main focus of this literature review will be the hollow core slabs especially composite action of the hollow core slabs. In relation to this composite action of other slab elements will also be discussed.

2.2. Composite action due to concrete slab on steel and materials other than concrete

Composite action has been seen to significantly enhance the flexural characteristics of the elements. In a study (Fam & Skutezky 2006) on rectangular glass fiber reinforced polymer seven beam specimens were used out of which four where considered as having composite action with concrete slab. Tests were done using a rectangular glass fiber reinforced polymer over which a concrete slab was placed to act as a composite. In this case however dowels from the GFRP tube beam was extended to the concrete slab to enhance the composite action.

Deflection responses were considered to assess the flexural behavior of specimen beams. It was found the composite action increased the ultimate loads by more than 30% and stiffnesses by more than 80%.

Another composite type of slab system is the steel reinforced concrete slim floor systems. In SRC or the steel reinforced concrete system, the asymmetrical steel beams are embedded in the concrete.

In another investigation (Yu et al. 2019) a test setup of 6 SRC beam types were conceived and erected. The figure below indicates the type of beams considered.

Specimen ID	Specimen size (mm) L × B	Specimen height, H (mm)	Shear span ratio	Type of steel shape	Steel size (mm)	Cubic strength of concrete (MPa)	Test setup
SRC-1	2700 × 900	450	3.0	H-shaped	200 × 100 × 5.5 × 8	53.3	One-point loading
SRC-2	2700 × 900	350	3.0	H-shaped	200 × 100 × 5.5 × 8	53.3	Two-point loading
SRC-3	2700 × 900	260	3.0	H-shaped	150 × 75 × 5 × 7	53.3	Two-point loading
SRC-4	2700 × 900	300	3.0	H-shaped	150 × 75 × 5 × 7	53.3	Two-point loading
SRC-5	2700 × 900	300	3.0	H-shaped	200 × 100 × 5.5 × 8	53.3	Two-point loading
SRC-6	2700 × 900	260	3.0	Castellated	226 × 75 × 5 × 7	53.3	Two-point loading

The numbers in the steel size represent total height, flange width, web thickness, and flange thickness in order.

Figure 1 – Types of beams considered (Yu et al. 2019)

A plane section was theorized and design was based on plasticity theory. As per the test results, the specimens satisfied the beam theory by Euler–Bernoulli. During loading it was noted that plane sections remained plane. All the six specimens were of composite structure and all of them showed good bondage between steel and concrete elements resulting which the flexural capacity was increased considerably. It was found that concrete and steel members were acting in tandem. With the rise in the specimen sizes and shape the flexural capacity showed substantial increase.

In a composite element of a steel girder and concrete topping slab, during the finite element analysis, the elements can even be analyzed separately (Si & Au 2011). An investigation (Liu et al. 2019) done on the sagging moments of steel composite concrete section also shows how the composite action increases the flexural action of the specimen. Among the four objectives, the first objective of the investigation was to probe via a lab study the hogging moment of 24 steel concrete composite beams which are simply supported and to assess their flexural capacity. Out of the 24 specimens, loading pattern in which 22 were dynamic cyclic and the remaining two were loaded in monotonic loading pattern. Two specimens named SCB19 and SCB 20 were loaded monotonically.

For continuous composite beams, the hogging moments can be found near the middle or inner supports and for beams which are fixed, the hogging moments can be found adjacent to vertical supports. In the investigation though, the specimens were simply supported and the hogging moment was determined at the interior supports. The effect of shear connection or the number of connectors and diameter of connectors were also studied.

After the tests, it was found that the hogging moment capacity had significant improvement through composite action. Factors such as the number of shear connectors that is the number of studs had a positive outcome in flexural capacity whereas the stud diameter had minimal effect on the flexural capacity. The presence of longitudinal and transverse reinforcement also had substantial impression in the hogging moment capacity.

Below table shows the specimens and their properties that were used in the test

No.	Loading mode	l (mm)	w_c (mm)	h_c (mm)	w_s (mm)	h_s (mm)	d (mm)	η	ρ_{st} (%)	ρ_{sl} (%)	M (kN)
SCB1	Dynamic cyclic	3000	650	75	258	140	13	1.44	0.62	3.47	120
SCB2	Dynamic cyclic	3000	650	75	258	140	13	0.55	0.62	3.47	121
SCB3	Dynamic cyclic	3000	650	75	258	140	13	1.44	0.62	3.47	158
SCB4	Dynamic cyclic	3000	650	75	258	140	13	1	0.62	3.47	146
SCB5	Dynamic cyclic	3000	650	75	258	140	13	0.55	0.62	3.47	132
SCB6	Dynamic cyclic	3000	650	75	258	140	13	2.64	0.62	1.89	131
SCB7	Dynamic cyclic	3000	650	75	258	140	13	1.83	0.62	1.89	123
SCB8	Dynamic cyclic	3000	650	75	258	140	13	1.01	0.62	1.89	120
SCB9	Dynamic cyclic	4000	1000	100	408	258	13	3.14	0.38	1.58	390
SCB10	Dynamic cyclic	4000	1000	100	408	258	16	3.25	0.38	1.58	399
SCB11	Dynamic cyclic	4000	1000	100	408	258	19	3.22	0.38	1.58	395
SCB12	Dynamic cyclic	4000	1000	100	408	258	16	2.26	0.38	1.58	392
SCB13	Dynamic cyclic	4000	1000	100	408	258	16	4.24	0.38	1.58	405
SCB14	Dynamic cyclic	3800	800	120	100	200	16	1.83	0.32	2.51	207
SCB15	Dynamic cyclic	3800	800	120	100	200	16	1.59	0.32	2.51	198
SCB16	Dynamic cyclic	3800	800	120	100	200	16	1.3	0.32	2.51	193
SCB17	Dynamic cyclic	3800	800	120	100	200	16	1.06	0.32	2.51	189
SCB18	Dynamic cyclic	3800	800	120	100	200	16	0.83	0.32	2.51	187
SCB19	Monotonic	3800	800	120	100	200	16	1.74	0.32	1.88	172
SCB20	Monotonic	3800	800	120	100	200	16	2.22	0.32	1.47	165
SCB21	Dynamic cyclic	3800	800	120	100	200	16	1.3	0.20	2.51	200
SCB22	Dynamic cyclic	3800	800	120	100	200	16	1.3	0.43	2.51	211
SCB23	Dynamic cyclic	3800	800	120	100	200	16	1.3	0.59	2.51	206
SCB24	Dynamic cyclic	3800	800	120	100	200	16	1.3	0.78	2.51	224

Figure 2 – Specimen properties (Liu et al. 2019)

Another research (Hsu et al. 2014) used cold formed steel joists with concrete slab as composite action. The components of this composite section were cold-formed furring used as shear connector for composite action, reinforced concrete slab on the top and cold-formed steel joists placed alongside each other. In the test specimens used in this research, conventional steel studs are replaced by cold-formed furring to demonstrate how steel studs are not always a pre requisite to attain composite action. To secure the furring shear connector with the steel joists and metal deck hex screws were used. It is by the means of bon-slip mechanism, the horizontal shear resistance is transferred from the top concrete slab to the joists. Since there is more segregation between the composite elements, compared to conventional elements these showed more noise control.

Six specimens were used for testing. Below table shows the type of specimens used for testing.

Specimen	Studs size	Span length (ft) (m)	Type of fastener	Concrete thickness (in. × in.) (mm × mm)	Concrete strength, f'_c (psi) (MPa)	Remark
CB1	600S200-68	12	#10	3" × 36"	2700	Normal Weight Concrete (145 pcf or 23.87 kN/m^3)
		3.6		76 × 915	18.62	
CB2	600S200-68	12	#10/#12	3" × 36"	2700	
		3.6		76 × 915	18.62	
CB3	600S200-68	12	#10	3.5" × 36"	3200	
		3.6		76 × 915	22.06	
CB4	600S200-68	12	#10/#12	3.5" × 36"	3200	
		3.6		76 × 915	22.06	
CB5	600S200-68	12	#10/#12	3.5" × 36"	3200	
		3.6		76 × 915	22.06	
CB6	600S200-68	12	–	–	–	No concrete slab
		3.6	–	–	–	

Figure 3 – Types of specimen (Hsu et al. 2014)

Four-point loading were used for the testing with span of the specimen being 3.6m. Three of the test specimens were composite section, two non-composite and one section without any concrete topping at all.

In the entire tests conducted, the ultimate strength and ductility of the composite sections were superior to non-composite or built up sections. Ultimate strength increased by 14-38% whereas ductility was increased by 56-80% in composite sections. It was found that the entireness of the structure was maintained by furring shear connector.

(Baldassino et al. 2019) examined the long-term effects on the composite beams. Both specimens were of same configuration. The specimens comprised steel beam HEB200 and concrete topping which was T-shaped. The system was simply supported with a total length of 6300mm. The first sample was not loaded and the second sample was continuously loaded for a fixed time after which both the samples were tested for ultimate load. Maximum loads were 536.1KN and 562.7KN for first and second sample after the initial long-term loads were released and reloaded. This study indicates the service capability of composite structures. Creep effects were minimal considering the ultimate capacity of the specimens.

2.3. Composite action due to concrete slab on non-hollow core slab concrete elements

As we have seen in the previous section composite action has been proved quite efficient in non-hollow core slab concrete elements also. Tests (Kim et al. 2017) were conducted on a composite of precast concrete beam and cast in place beam. The test was done to assess the shear performance and the contribution of shear reinforcement in the composite action. It was found that the composite action helped in the shear characteristics of the elements and it was safe to consider that the average concrete compression strengths of cast in place and precast concrete with the specimen considered as a whole element. This was assessed after the testing of 15 simply supported test samples. Two vertical loadings were provided at the center during the testing of the composite elements. Another experimental study (Yang et al. 2017) on partially precast concrete beams showed that the flexural capacity of the composite slab was comparable to that of cast in place concrete slab.

Precast concrete sandwich panels are used extensively as wall due to its insulating capacities, but it can also be used as composite one-way slabs. A research (Daniel Ronald Joseph, Prabakar &

Alagusundaramoorthy 2017) was done on precast concrete sandwich panels for their use as one-way slabs. Out of the 150mm thick sandwich panels only the outer layer of each 25mm were concrete and the internal 100mm was extruded polystyrene. Since the major internal part was nonstructural element, truss shaped reinforcement bars were used as shear connectors along the span of the element for composite action. It was found even in this case the composite action was completely attainable. Load- deflection response was used to determine the composite action of the elements. It was also concluded that the flexural results were in agreement with the behavior of traditional cast in situ reinforced concrete one-way slabs. Bond strength between different elements has a significant role in the composite action. Bond strength depends upon the roughness of the concrete surface which can be measured using laser based devices through optical techniques (Santos & Júlio 2013). Gadri & Guettala (2017) in their study had found that flexural strength can be enhanced by the increased roughness in the interface. In a study (Lam, Wong & Lee 2019) on semi- precast slabs which had differential shrinkage and was applied with flexural loads also points to the non- requirement of reinforcement steel at the interface to attain composite action. When a research was done using steel bars for connecting in the interface (Niwa et al. 2016) it was noted that increasing the ratio of reinforcement from 0.51% to 1.01% actually caused a reduction in the shear strength. In a different investigation (Cho, Shin & Kim 2017) it was also observed that in a composite slab construction the construction productivity raised by 1.7 times than conventional cast in place slabs. However, it was observed in the research by Cavaco & Camara (2017) it was noticed that cracks can be developed in the interface in the tension area in the hogging part of composite slab system.

2.4.Hollow core Slabs as structural elements

2.4.1 Load Calculation

As all other structural elements hollow core slabs should be analyzed properly for their loading distribution and to predict their structural performances. Hollow core slabs are assumed to be one-way slabs and the slabs are arranged one after the other with minimum or no gap. The gap between the hollow core slabs are typically filled with concrete grouts. Each hollow core slabs are routinely designed assuming the load on individual hollow core slabs only. But the loads are distributed to nearby hollow core slabs also especially when the concrete screed is provided. This can be easily demonstrated by the way in adjacent hollow core slabs are deflected when the load is applied on the nearby hollow core slabs. Shear strength of prestressed concrete structures are generally confined to the maximum web crushing equation (Olalusi & Kolawole 2018) so that ahead of the yielding of reinforcement the crushing of concrete can be avoided. A research by XPark et al. (2019) shows that the web-shear capacity reduction following AC1-318-08 code was extremely conservative. Nevertheless, this is followed in everyday calculation of HCS.A numerical model was developed (Bernardi et al. 2016) in which it was assumed the hollow core slab units by the virtue of rotational hinges are attached with one another. It is even recommended to provide topping for achieving this hypothesis. It can be safely concluded that the presence of cast in place concrete topping increases the chances of uniform load distribution and proper analysis of structure. By the virtue of its capacity to imbibe energy from blast loads (Maazoun et al. 2017), reinforced concrete hollow core slabs are also used extensively in blast resistant buildings. The blast capacity of HCS can be further increased by using carbon fiber reinforced polymer strips as externally bonded reinforcement (Maazoun et al. 2019). This helps in considerably raising flexural strength and stiffness during blasting conditions. Hollow core slabs can even be used as vertical elements for shear wall system (Xiong et al. 2018) but it has to be noted that conventional reinforced cast in situ shear walls will have a higher shear strength than HCS.

2.4.2 Natural Frequency of hollow core slabs

The depth of structural screed also helps in the vibration behavior of the hollow core slabs. An investigation (Frăţilă & Kiss 2016) on the finite element analysis and an experimental test on hollow core slabs with varying thicknesses and structural screeds argues that that the results between the analysis and test results were highly matching. Natural frequency of the hollow core slab with screed was found to have higher natural frequency than the one without. It was also observed that the with the increase in screed thickness the natural frequency also increased. Another fact to be noted was that the span of the system could be increased with the increase in structural screed thickness. However as indicated in another paper (Jendzelovsky & Zabakova Vrablova 2015) it can be found that the natural frequencies of hollow core slabs are lesser than that of solid slab which to certain extent can be compensated only through structural screed. In another research (Liu et al. 2017) it was established that the mode shapes of hollow core slab elements with the structural screed and without structural screed were indistinguishable. A study (Liu, Battini & Pacoste 2019) was conducted on the impact of single pedestrians in hollow core slabs of 10m spans and it was noted that the material properties of the hollow core slabs easily affected the vibrations.

2.4.3 Fire resistance of hollow core slabs

Precast concrete slab elements have high durability under fire conditions. In a study (Gravit et al. 2017), it was found that structural integrity of the slab was not lost even after 180 minutes of testing under fire in which the temperature was raised up to 1100^0c. Hollow core slabs are also considered to be providing good fire resistance. It has been observed that under service loadings hollow core slabs can uphold under fire for two hours (Shakya & Kodur 2015). Cover of concrete plays a significant part in the fire resistance. In a paper, (Chang et al. 2010) the width to floor span ratio was explored for its effect in the hollow core slab's immunity to fire. A simplified model was considered during the analysis in which the structural screed along with the hollow core slabs were assumed as beams and obtained good results. From the paper we can deduce that to be in safer side, table corresponding to flat slab from Eurocode 2 should be used to determine the effect of aspect ratio in fire resistance of hollow core slabs. It was found that (Hertz, Giuliani & Sørensen 2017) the bottom flanges of the hollow core slabs are more susceptible to cracking and failure of the hollow core slabs mainly occur in bottom flanges. As most of the hollow core slabs are only having prestressing strands embedded in the concrete it was crucial to observe their characteristics during fire. A study (Aguado et al. 2012) validates the position that wire strands performs better than reinforcements during the course of fire. Voids of the hollow core slabs have also significant influence in the fire resistance of hollow core slabs. It can be observed (Albero et al. 2018) that increasing the convexity of the curvature in the rear end of the voids increases the fire resistance of hollow core slabs. The strength of bonding between the strands and the concrete is reduced during the fire at very high temperatures but it is mainly due to the variation in concrete material properties (Khalaf & Huang 2016). The manner in which hollow core slabs fail under fire has a direct link with the thicknesses of the slabs (Kodur & Shakya 2017). Shear failure characterizes for the deeper hollow core slabs (350 and 400) whereas flexural failure is dominant for the slender hollow core slabs (150 and 200). Another factor which affects the failure of hollow core slabs during fire is the order of loading (Shakya & Kodur 2017), a pointed load or a heavy load near the support may cause shear failure before flexure. It is also worth noting that cores in the hollow core slabs are generally circular rather than square because the circular cores provide 13.4% ultimate strength more than square cored hollow core slabs (Al-Azzawi & Abed 2017).

2.4.4 Hollow core slabs without topping

Even though the hollow core slabs are used in UAE are almost entirely with screed substantial number of studies were done with the hollow core slabs without topping. Even without topping hollow core slabs which can be considered as beams for analysis, shows very good structural performance. Due to its peculiar shape and stresses the nature of shear stresses has always been a subject of debate. An investigation (Nguyen, Tan & Kanda 2019) had established that the raise in web thickness in turn raised web shear capacity also of the hollow core slabs. It was also concluded that when the strength of concrete was escalated from 40 to 70 MPa the web shear capacity showed a marked improvement as good as 2.4 times. At the same time, it was noted that raise in prestressing force caused the decrement in web shear resistance. Hollow core slabs with more thickness show more shear cracks as per another paper (Brunesi, Bolognini & Nascimbene 2015).

The same was also confirmed in another investigation (El-Sayed, Al-Negheimish & Alhozaimy 2019). As per another study (Tawadrous & Morcous 2018) primarily on deep hollow core slabs, it was noted that since the slabs were devoid of any reinforcements, compressive strength of concrete was significant for shear strength. Apart from concrete compressive strength, amount of prestressing, dimensions of the element, shear span to depth (a/d) ratio, and length of bearing supports also played significant roles in shear strength of the hollow core slabs. Hollow core slabs are generally produced using dry cast concrete but recently self-compacting concrete is gaining popularity among the producers. An investigation by Al-Negheimish et al. (2018) confirms that even though the immediate deflections in self HCS using self-compacted concrete was higher, the long-term deflections matched with those of dry cast concrete HCS.

Damaged hollow core slabs were exposed to shear tests (Schacht, Marx & Bolle 2017) and it was found that only extremely deteriorated hollow core slabs needed replacement and the remaining could be used with minor repairs. Shear capacity of hollow core slabs remained intact to the required amount even after moisture penetration and chloride contamination. Shear strength of hollow core slabs can be further increased by newer techniques like fiber reinforcements also. Investigations (Cuenca & Serna 2013)were done on this effect and found that fiber reinforcements can be embedded in the hollow core slab composite with minimal technical issues and the resultant specimen showed high ductility and shear strength than the conventional hollow core slabs. As determined through load-deflection behavior (Al-Shaarbaf, Al-Azzawi & Abdulsattar 2018) , bending property of hollow core slabs are better than solid slabs and as such traditional bending strength formula can be utilized in the case of hollow core slabs also. Hollow core slabs are designed as uncracked sections and it proves to be a limitation in many a scenario , this can be overcome by using macro synthetic fibers as reinforcement (Kankeri et al. 2019). It was found that by using synthetic fibers helped in lowering the crack widths and raised the

Hollow core slabs can also be used for ventilated Building-Integrated Thermal Energy Storage (BITES). The cores can be used for air circulation (Xu et al. 2014). The number of cores in hollow core slabs also has a major impact in the structural properties of HCS (Al-Azzawi & Abdul Al-Aziz 2018). The deflection raises by 10.77% and ultimate load reduces by 8.91% if the number of cores escalated from 3 to 5. Hollow core slabs provide higher flexural strengths than the traditional solid slabs of same weight. This was established in a research (Wariyatno, Haryanto & Sudibyo 2017)and it can be concluded that the usage of hollow core slab can also help in the foundation sizes in this regard. Hollow core slabs can be cracked during the construction process during delivery or even during erection. Of all the cracks, spalling cracks (Vadzim Parkhats 2018) should be taken care of immediately as it is the most damaging and they hugely increase in size swiftly. Even though hollow core slabs are highly capable for positive moments as it is typically considered as pinned supports, there are some cases when the negative moments also have to be considered during their design. There are numerous methods in which the negative moments can be increased in the hollow core slabs out which a method was proposed also by using carbon fiber reinforced polymer strips (Hosny et al. 2006). It was realized that carbon fiber reinforced polymer strips can be used at the top of hollow core slabs to increase its negative moment. The negative moment could be elevated from 0 to 277% through this method and a further increase to 574% can be attained when in the end 1.5 m the bonding between concrete and prestressing strands are severed using a duct tape. Hollow core slabs are also preferred to the traditional cast in place slabs due to its deflection characteristics. Due to the camber generated in the initial stages the final downward deflection of hollow core slabs is always less than cast in place slabs. Hollow core slabs made with self-compacting concrete which is rather a newly used in hollow core slabs instead of the traditional dry cast concrete was tested for their long term deflection for over 730 days by (Long-term deflection of prestressed SCC hollow core slabs) and it was found that for hollow core slabs of showed comparable long term deflections for slabs with both concretes. But it has to be noted that the 470mm hollow core slab showed 15% more instantaneous deflection. In the case of providing openings in the hollow core slabs it is always recommended to provide it at the center of the HCS as it will ensure that there is a ductile failure (Heiza, Elkholy & Meleka 2018)

2.4.5 Hollow core slabs with structural screed

Composite action of hollow core slabs has been substantiated by recent studies. An investigation (Baran 2015) was done in this regard using hollow core slabs of 150mm thick and a structural screed of 50mm. 5 specimens were used for the testing with three specimens having the standard 1.2m width out which one was without topping. Remaining two specimens were 0.55m in width, one with 50mm topping and the other without topping. Hollow core slabs were simply supported at the ends and a uniform loading was applied. It was found that in 1.2m width hollow core slabs, the ultimate moment capacity was increased by 23% whereas the increase in ultimate moment was lesser .55m width hollow core slabs. Under uncracked condition, it was noted that the composite action was intact and the composite action started losing only once the cracking started after which the slabs and topping started acting as two separated entities. The increase in ultimate moment of the hollow core slabs was also illustrated in another study (Kankeri & Suriya Prakash 2017). It was observed that the flexural capacity was increased by 60% than the hollow core slab without topping. In this case also 150mm hollow core slabs were used with 50mm structural screed. A proposal (Adawi, Youssef & Meshaly 2016) was made on an analytical solution for the interfacial stresses in the composite action. It was concluded that the North American Codes are more conservative during the analysis of the stresses during composite action as compared to the analytical solution proposed. By using glass fiber reinforced concrete of 65mm thickness (Qureshi 2018), it was observed that the flexural capacity can be improved by 50%.The surface of the hollow core slabs is intentionally roughened so that sufficient bonding is there between the hollow core slabs and the topping. Before the cast in place topping concrete is poured, the surface of the hollow core slabs should sufficiently clean of laitance so that it may not affect the interfacial shear strength (Mones 2012) . Hollow core slabs which are machine finish or smooth finish are typically used in boundary walls. Adawi, Youssef & Meshaly (2015) investigated on the composite action of hollow core slabs with machine cast finish or relatively smooth finish and even though the roughness was very less than the values recommended by North American design standards, it was observed that the bond strength between the topping and the hollow core slabs were well within the limits. A similar investigation was conducted by Ibrahim et al. (2016) in which twelve hollow core specimens were tested. Hollow core slabs were cut longitudinally to simulate joints as found in the actual situation. Simply supported span considered was 4.3m and a topping of 75mm to 80mm were used in the test specimens. Half of the specimens were rough finished while the other half were smooth finished. In this situation also 150mm thick hollow core slabs with a 100mm diameter hollow cores were used for the test. It was noticed that both the roughly finished and smoothly finished hollow core slabs accomplished full composite behavior albeit the composite action was more prominent in roughly finished hollow core slabs. In another research (A. Youssef & Aiham 2013) on HCS with machine cast finish with mean surface roughness of 0.355mm which is way less than recommended roughness it was concluded based on the test results that the surface can be considered as bonded topping. However, in a study by Mones & Breña (2013) it was observed that the interface shear strength increased with an increase in roughness of the HCS. The longitudinal joint shear capacity can be ignored for interface shear calculations (Derkowski & Surma 2015). It was also noted in an investigation by Kankeri, Suriya Prakash & Pachalla (2018) that composite hollow core slabs strengthened by hybrid FRP and overlay technique can increase the overall capacity by 100% without impacting ductility. By using shear keys from the HCS in the interface the ultimate loads on the hollow core slabs can be increased further and it can attain up to an increase of 59.6% (Kankeri, Chellapandian & Prakash 2017) from non-composite sections but these are not generally preferred due to their complexity of manufacture.

2.5.Methodology of tests on Hollow core slabs

The test methods adapted in the researches above and the ones which will be discussed further are based mainly on the assumption that the slabs are simply supported. In actual conditions also the hollow core slabs are assumed as simply supported section unless cantilever sections are required which are extremely rare. One of the earliest tests on the hollow core slabs done by Becker &

Buettner (1985) in which 200mm and 254mm thick slabs were tested. Since the test was mainly for determining the shear capacity, point loads were applied towards the support of the slabs. The test setup was as shown in the figure below.

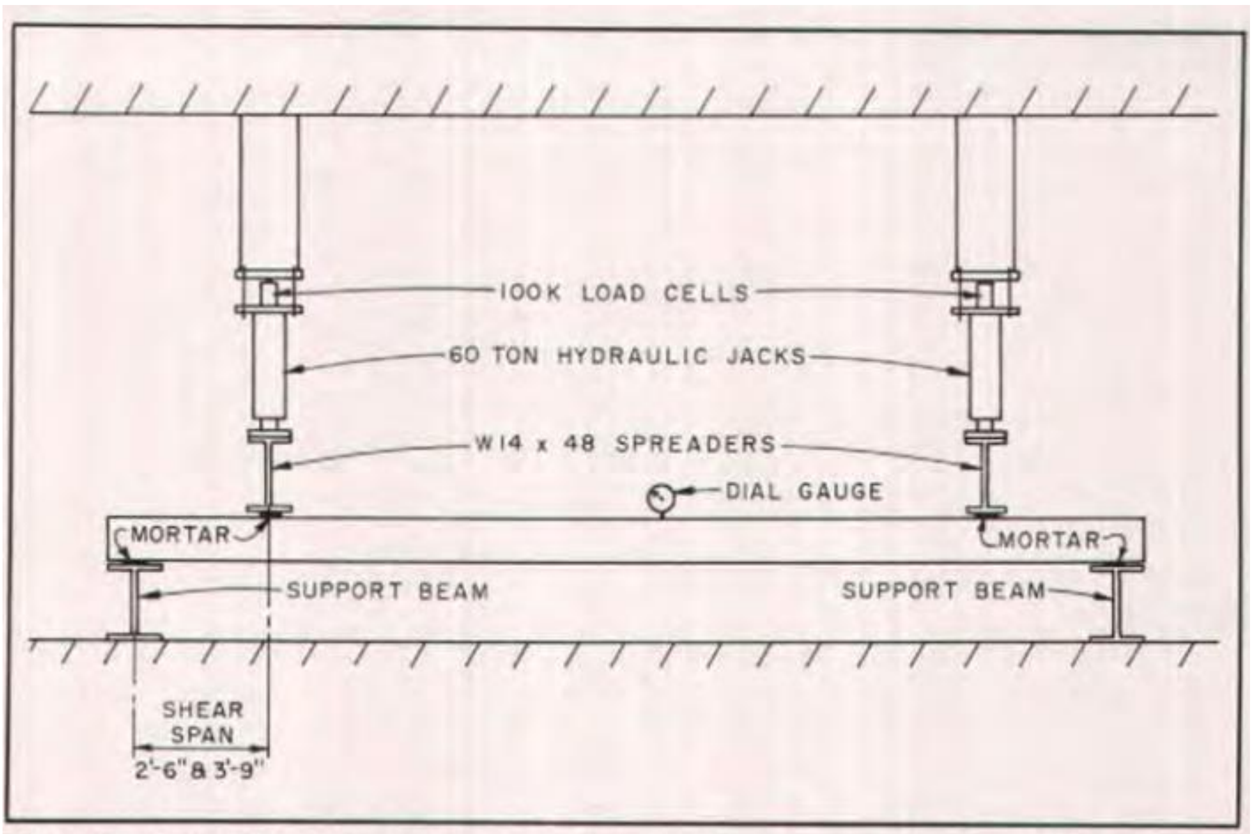

Figure 4 – Test setup (Becker & Buettner 1985)

Hollow core slabs with thicknesses 200mm, 250mm and 300mm of 2.5m and 3m were tested by Rahman et al. (2012). In this case also a similar loading setup was adopted. The hollow core slabs were considered as simply supported and was supported on I beams at the ends. In this test though the loading was applied in at the center since both flexure and shear capacity were assessed.

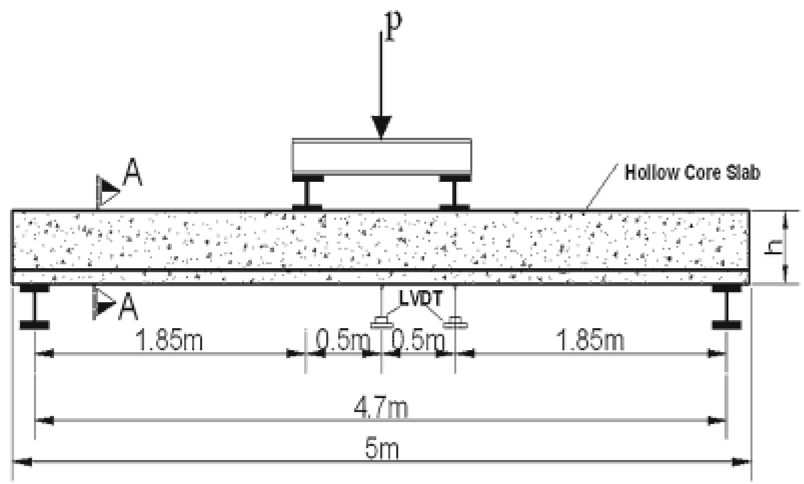

Figure 5 – Test setup (Rahman et al. 2012)

Composite section was considered in the test setup in another investigation (Haruna, Gora & Malami 2018) in which HCS of 150mm thick was only used with a 50mm topping. Roller supports were provided at both ends and the span considered was 4.6m. even thought composite section was considered, only one hollow core slab was used in the test which does not indicate the actual site condition for composite HCS. Hollow core slabs strengthened with glass fibre reinforced polymer and with opening were investigated by Pachalla & Prakash (2017) for their load resistances and failure modes. In this case also a single hollow core slab albeit without topping was considered. The load setup is similar to those discussed earlier wherein two concentrated loads were applied through I beam sections near to the center of the slab. The displacements were measured at three points, one at the center and two near the end supports using a linear variable displacement transducer. Four different types of toppings were considered in a test (Meleka, Nabil & Heiza 2018) with a hollow core slab of 160mm thickness. 1st with ordinary reinforced concrete without steel anchors, 2nd concrete with steel anchors, 3rd with fibrous concrete topping and the 4th with ferrocement topping. This time also only single HS with topping was loaded on simply supported condition. This setup was also similar to the previous tests with two-point loads near the center being applied. Three gauges were provided below the HCS to measure the deflections. All the four cases showed better flexural and shear characteristics when compared to the HCS without topping.

2.6. Conclusion

Composite action helps in reducing the sizes of hollow core slabs and in turn the whole building weight and effectively reducing the foundation sizes. The studies we have discussed above clearly shows the effectiveness of composite action and indicates how composite action of hollow core slabs are reliable in uncracked sections. Even though there are some studies that suggests that smooth finished hollow core slabs can be used for composite action, in this investigation only the hollow core slabs with rough finishes shall be considered. Load testing method employed in most of the investigations consider only single hollow core slabs and provide only two-point load near the center. This does not mirror the actual site condition in which multiple HCS are laid together with topping which helps the HCS together to act as one unit. Loadings are also confined to two points in the whole section which is not the usual site condition.

Chapter 3
Research Methodology

3.1.Research Approach

As seen from the literature review hollow core slabs can be considered as a composite section with structural screed. The research has been done with two of the most widely used hollow core slabs that is ELEMATIC sections with 150mm thick and 265m thick. Hollow core slabs were tested under factory conditions as per the procedure specified in ACI318M-2011, chapter 20. The results of the load tests will be compared with the analysis results obtained through the software Concise Beam which is the most widely used software for the design of Hollow Core Slabs in precast industry in the United Arab Emirates. This method was adapted so that the test results and the analysis will be compatible with the Industry standard practices in the UAE.

3.2.Hollow core slab manufacturing

Hollow core slabs are produced in special molds due to which the geometry and the location of the prestressing strands cannot be altered. The number of prestressing strands can be reduced by not using strands in the specific area. It should be noted that the location of prestressing strands is fixed. The pouring of concrete is automated and as such dry cast concrete with zero slump is used during production. The length of bed is fixed. In this study the length of bed was 153m and the percentage of stressing 60%. Stressing details for 9.53mm diameter strands used in 150mm hollow core slabs are as shown below.

Area	55.1	mm^2
Weight	0.44	kg/m
Modulus of Elasticity	200000	N/mm^2
Tensile Strength (fpu)	1860	N/mm^2
Final Prestressing Force 60% of fpu "Pf"	61.9425	KN
Inch/Inch Elongations = (Pf * L)/(As *Es)	0.00562	mm/mm
Factory Bed Length (Stressing Plate to Stressing Plate)	153	m
Final Force	61.9425	KN
Final Elongation	860	mm

Table 1 – 9.5mm diameter strands elongation

Stressing details for 12.7mm diameter strands used in 265mm hollow core slabs are as shown below.

Area	99.2	mm^2
Weight	0.78	kg/m
Modulus of Elasticity	200000	N/mm^2
Tensile Strength (fpu)	1860	N/mm^2
Diameter 12.7 mm Strand	269700	lbs/in^2
Final Prestressing Force 60% of fpu "Pf"	111.519	KN
Inch/Inch Elongations = (Pf * L)/(As *Es)	0.00562	mm/mm
Factory Bed Length (Stressing Plate to Stressing Plate) =	153	m
Final Force	111.519	KN
Final Elongation	860	mm

Table 2 – 12.7 mm diameter strands elongation

Average elongation required after stressing the strands is 860mm for both 150mm and 265mm as the bed length of 153m is used. Before the concrete is poured the strands are stressed and the required stress can be verified through the final elongation. Dry mix concrete is poured to the mold there after. After attaining a compressive strength of concrete of 35MPa (Cylindrical) the prestressing strands are cut after which the hollow core slabs are cut to required spans. Hollow core slabs are transported by crane to stockyard after which further curing is done.

Hollow core slab during the casting itself is intentionally roughened on the top so that it can attain enough bonding with the topping concrete. Intentional roughening is done through brooms. A polystyrene stopper is provided in all the cores for the both the hollow core slabs at 150mm from the ends in order to prevent the flow of concrete inside the cores during the casting of structural screed

The geometry of hollow core slabs and the location of prestressing strands are as per the below figures.

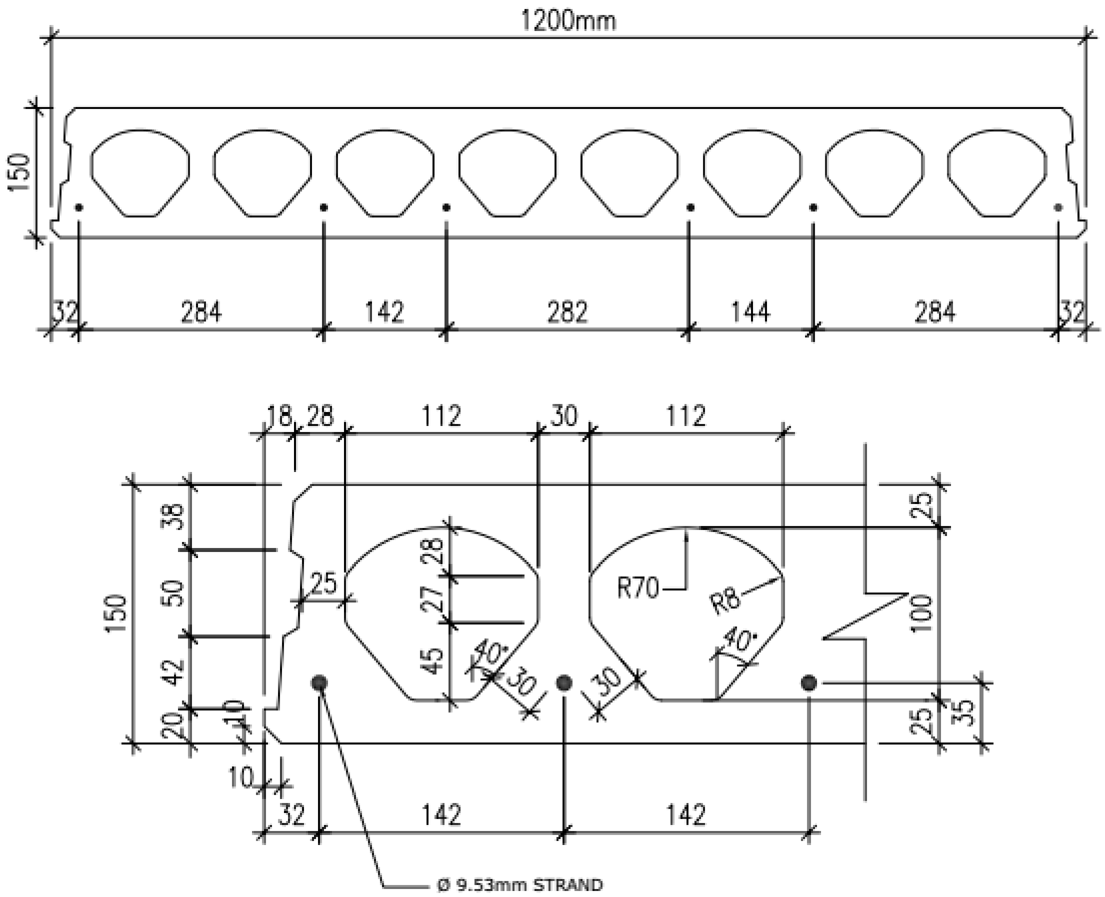

Figure 6 – Geometry of Hollow core slab 150mm

SLAB SECTION AND MATERIAL PROPERTIES			
NET AREA..........................	107,400 mm^2	SLAB SELF WEIGHT.....................	2.24 kN/m^2
MOMENT OF INERTIA..........	2.87E+08 mm^4	JOINT FILLING	0.11 kN/m^2
CENTROID FROM SLAB BOTTOM	73 mm	TOTAL SELFWEIGHT	2.35 kN/m^2
SECTION MODULUS, TOP.......	3.73E+06 mm^3	CUBE STRENGTH OF CONCRETE	60 N/mm^2
SECTION MODULUS, BOTTOM.	3.94E+06 mm^3	CONCRETE STRENGTH AT TRANSFER	42 N/mm^2
WEB WIDTH	259.99 mm	DENSITY OF CONCRETE	2,500 kg/m^3
V/S RATIO	40.36	ULTIMATE STEEL STRENGTH	1,860 N/mm^2

Table 3 – Geometrical properties of hollow core slab 150

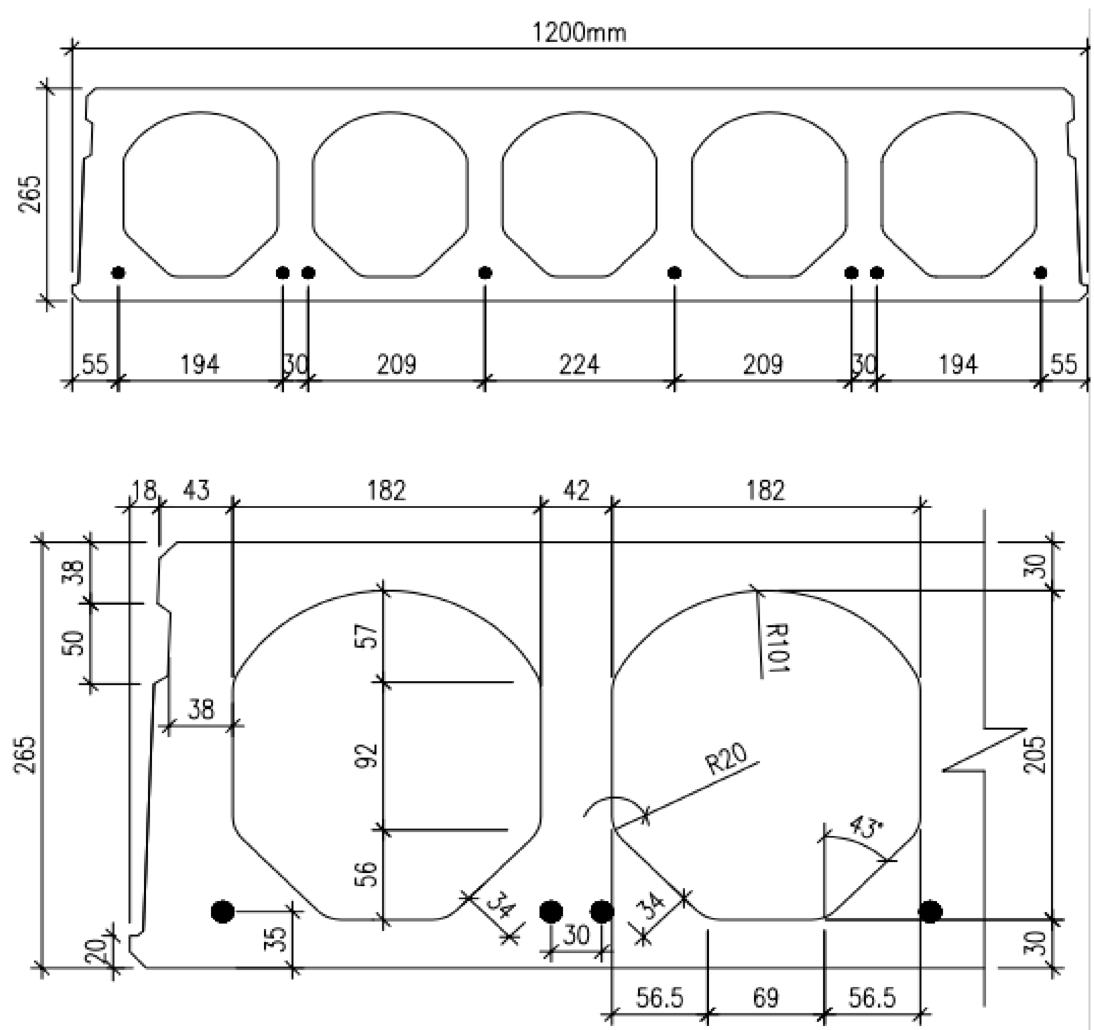

Figure 7 – Geometry of Hollow core slab 265mm

SLAB SECTION AND MATERIAL PROPERTIES					
NET AREA.........................	154,888	mm^2	SLAB SELF WEIGHT....................	3.23	kN/m^2
MOMENT OF INERTIA..........	1.39+09	mm^4	JOINT FILLING	0.19	kN/m^2
CENTROID FROM SLAB BOTTOM	131	mm	TOTAL SELFWEIGHT	3.42	kN/m^2
SECTION MODULUS, TOP.......	1.04E+06	mm^3	CUBE STRENGTH OF CONCRETE	60	N/mm^2
SECTION MODULUS, BOTTOM.	1.06E+06	mm^3	CONCRETE STRENGTH AT TRANSFER	42	N/mm^2
WEB WIDTH	262.47	mm	DENSITY OF CONCRETE	2,500	kg/m^3
V/S RATIO	53.68		ULTIMATE STEEL STRENGTH	1,860	N/mm^2

Table 4 – Geometrical properties of hollow core slab 265

3.3.Test Setup

Unlike what was typically used in the test setups of hollow core slabs as was seen in the literature review, the test setup in this research will be indicative of the actual situation at the site. The test setup will be larger in scale and as such three hollow core slabs will be arranged side by side. Since this setup will be larger than the usual test setups, cement bags will be used for loading the hollow core slabs after the screed is placed. Using of cement bags provides further advantage that the distribution of loads in the hollow core slabs will be more uniform unlike two-point loading near center of slab. This also ensures gradual loading in the system.

3.3.1 Placement of topping for 150mm hollow core slab

The support conditions are assumed to be simply supported. Two rectangular reinforced concrete beam blocks of 150mm which are designed to carry sufficient loads for the load test are placed with a span of 4m so that it can accommodate 3 hollow core slabs placed side by side. Concrete beam blocks will be placed at a spacing of 3m. After the supports have attained sufficient strength that is after a minimum of seven days the hollow core slabs are erected on the supports. The top surface of the hollow core slabs is sufficiently cleaned and roughed before pouring the topping concrete. The structural screed of A142 wire mesh is placed maintaining adequate cover for concrete. 8mm dia reinforcement bars are placed at 400mm c/c at bent up from the support to 600mm above structural screed. 2 numbers 10mm dia continuous bars are provided longitudinally above the screed at the end of the hollow core slab. A polystyrene stopper is provided at the end of the hollow core slabs so that the concrete will not flow inside the cores of the hollow core slabs. After the A142 wire mesh and the rebars are placed concrete is poured at one time simulating the actual condition at the site.

Loading arrangement for 150mm hollow core slabs is as shown below.

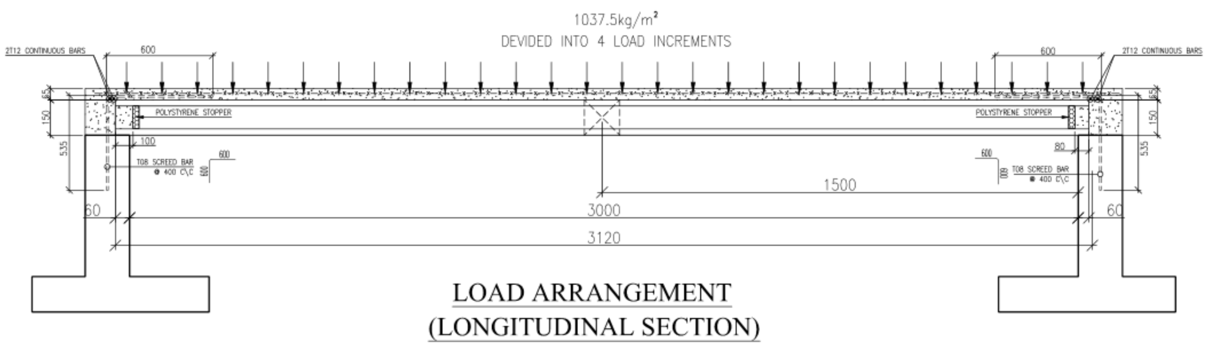

Figure 8 – Longitudinal section of loading arrangement HCS 150

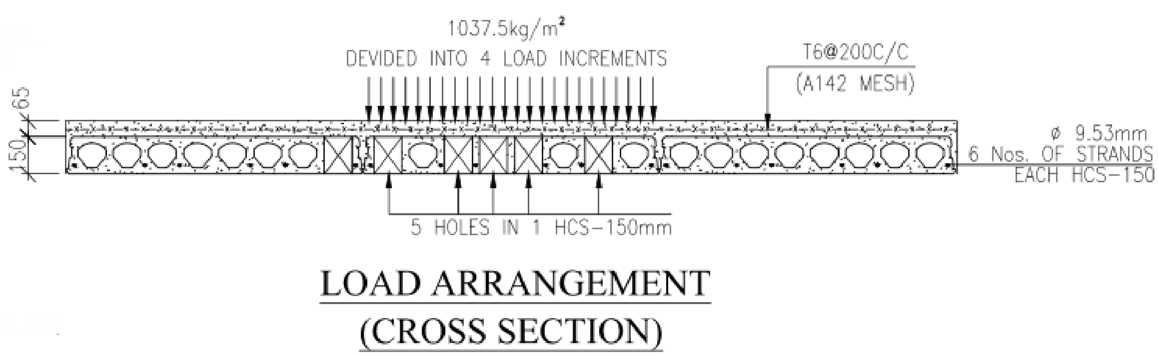

Figure 9 – Cross section of loading arrangement HCS 150

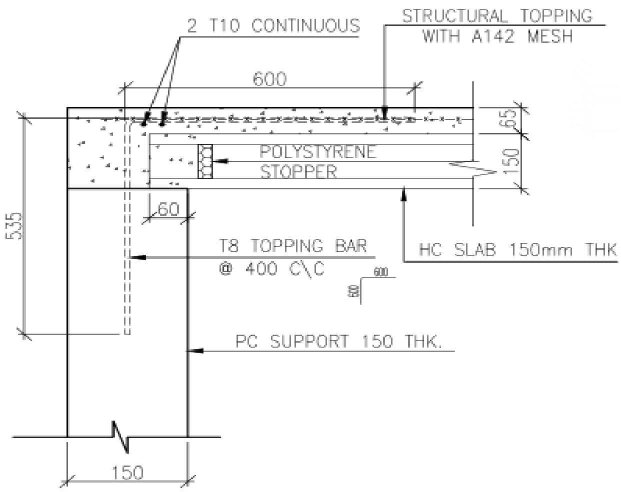

Figure 10 – Connection detail HCS 150

3.3.2 Placement of topping for 265mm hollow core slab

At both ends the hollow core slabs are supported by 250mm thick reinforced concrete block which has been designed to carry sufficient loads for the load test.

After the supports have attained sufficient strength that is after a minimum of seven days the hollow core slabs are erected on the supports. The top surface of the hollow core slabs is sufficiently cleaned and roughed before pouring the topping concrete. The structural screed of A393 wire mesh is placed maintaining adequate cover for concrete. 8mm dia reinforcement bars are placed at 400mm c/c at bent up from the support to 600mm above structural screed. 2 numbers 10mm dia continuous bars are provided longitudinally above the screed at the end of the hollow core slab. A polystyrene stopper is provided at the end of the hollow core slabs so that the concrete will not flow inside the cores of the hollow core slabs. After the A393 wire mesh and the rebars are placed concrete is poured at one time simulating the actual condition at the site.

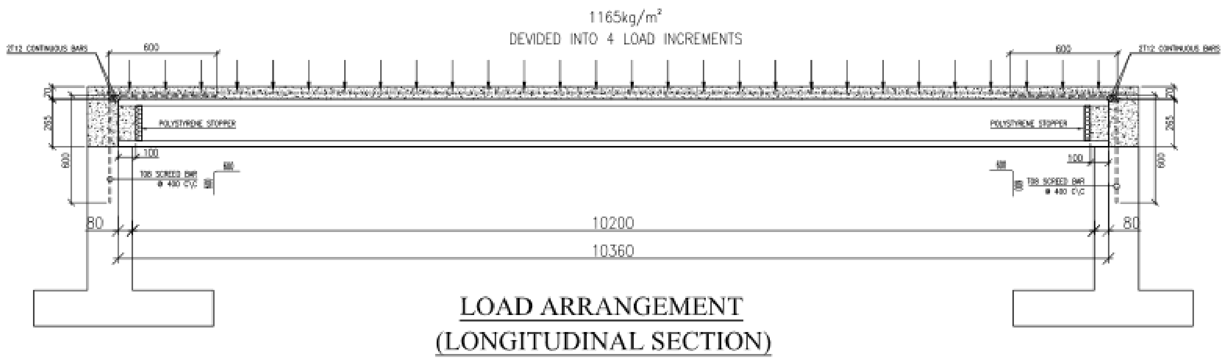

Figure 11 – Longitudinal section of loading arrangement HCS 265

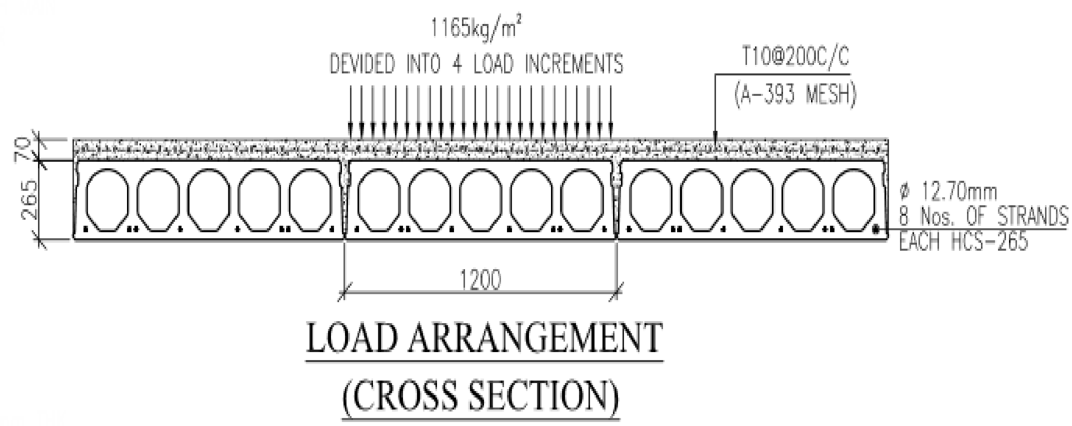

Figure 12 – Cross section of loading arrangement HCS 265

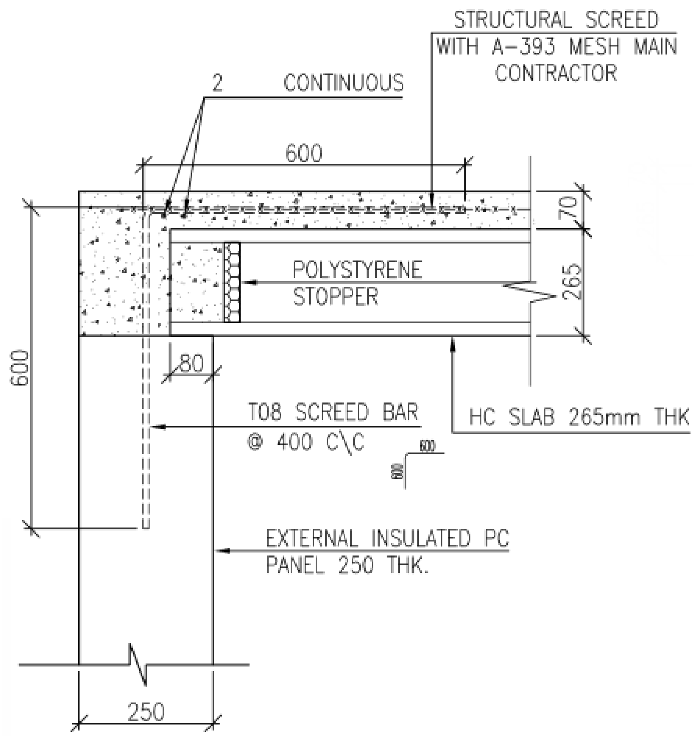

Figure 13 – Connection detail HCS 265

3.3.3 Loading sequence and loadings considered.

According to ACI 318M-11 20.3.2, the largest of the following loadings has to be used for load tests

(a) 1.15D + 1.5L + 0.4(Lr or S or R)

(b) 1.15D + 0.9L + 1.5(Lr or S or R)

(c) 1.3D

The dead load shown here does not include self-weight, only superimposed dead loads are considered. Super imposed dead loads, live loads and the spans of the hollow core slabs were determined as per the running project requirements in Abu Dhabi precast company. Number of cement bags were calculated separately since the span and the loadings and the span were different for both the hollow core slabs.

Loadings for 150mm hollow core slab is as follows

Design Floor SDL (D)	250 Kg/m^2
Design Floor Live Load (L)	500 Kg/m^2
Roof Live Load (Lr)	0 Kg/m^2
Snow Load (S)	0 Kg/m^2
Rain Load (R)	0 Kg/m^2
1.15 D+1.5L+0.4(Lr or S or R)	1037.50 Kg/m^2
1.15D + 0.9L + 1.5(Lr or S or R)	737.50 Kg/m^2
1.3D	325 Kg/m^2
Total Test Load Considered	1037.50 Kg/m^2
Total Load	3884 Kg
Weight of 1 cement bag	25 Kg
Required No. of cement bags	156 bags

Table 5 – Imposed loading on hollow core slab 150

Loadings for 265mm hollow core slab is as follows

Design Floor SDL (D)	750 Kg/m^2
Design Floor Live Load (L)	200 Kg/m^2
Roof Live Load (Lr)	0 Kg/m^2
Snow Load (S)	0 Kg/m^2
Rain Load (R)	0 Kg/m^2
1.15 D+1.5L+0.4(Lr or S or R)	1162.50 Kg/m^2
1.15D + 0.9L + 1.5(Lr or S or R)	1042.50 Kg/m^2
1.3D	975 Kg/m^2
Total Test Load Considered	1162.50 Kg/m^2
Total Load	14452 Kg

Weight of 1 cement bag	25 Kg
Required No. of cement bags	578 bags

Table 6 – Imposed loading on hollow core slab 265

3.3.3.1 Loading Sequence as per ACI 318M-11 section 20.4 and 20.5

The loading sequence followed will be as per ACI 318M-11 section 20.4 and 20.5. It is recommended that a single cycle of incremental load is employed when applying the uniformly distributed load. The maximum and the zero loads shall be held for 24 hours. Dial gauge is placed below the hollow core slab after the load setup is completed. In the cycle 1, Obtain the initial value of response measurements at least 1 hour before application of the first load increment. Hollow core slabs normally have significant camber because of the prestressing strands which helps in decreasing the effective deflection. Apply incremental load (25% of total load) of cement bags or water. After waiting for five minutes, record dial gauge readings. Again, an incremental load of (25% of load) cement bags are to be applied and the after waiting for 5 minutes, the dial gauge readings are to be recorded. These steps have to be repeated until final loading level is achieved. The maximum load should now be maintained for 24 hours. After 24 hours of maximum load, reading Δ_1 has to be recorded immediately after the cement bags should be removed. Now the test setup will be in zero loading condition and these zero loads should be maintained for further 24 hours. If the result does not meet acceptance criteria for cycle-1, a second cycle identical to cycle-1 is allowed by the standard. However, such repeat test shall be conducted not earlier than 72 hours after removal of the first test load.

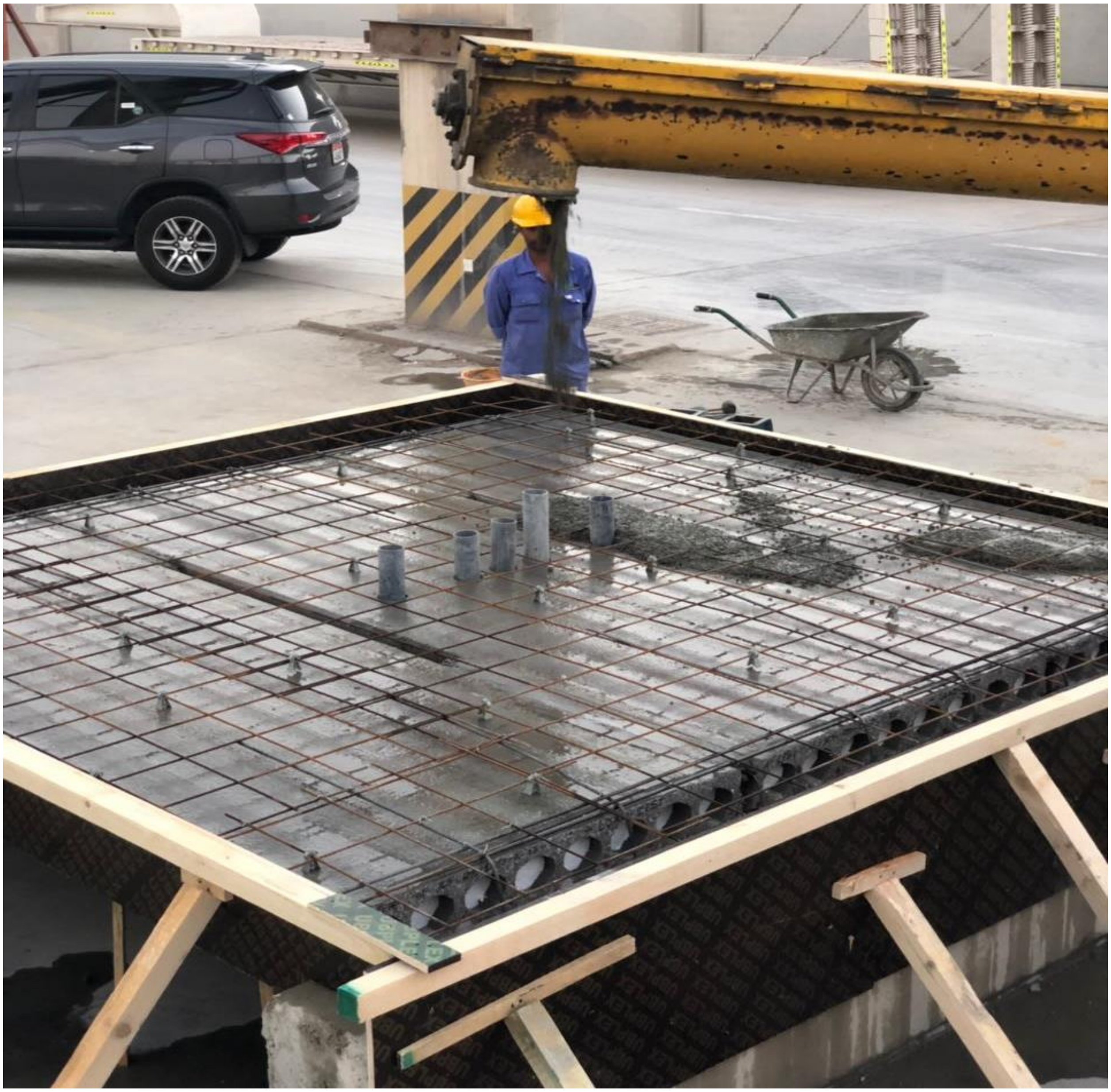

Figure 14 – Pouring Cast in situ concrete for HCS 150 test setup

Figure 15 –Test setup before the placement of wire mesh for HCS 265

3.4 Acceptance Criteria

ACI 20.5.2. When maximum deflection exceeds $L^2/(20000h)$, the percentage recovery must be at least 75% after 24 hours,

where:

Maximum deflection, $\Delta = L^2/(20000h)$ *Equation 20-1*

Residual deflection, $\Delta r = \Delta_1 / 4$ *Equation 20-2*

h = overall thickness of member (mm)

L = span of member under load test (mm)

Maximum deflection limit during load test of HCS 150:

$\Delta = L^2/ (20000h) = (3120 \text{ mm})^2 / (20000 \times 335 \text{ mm})$

Δ = 3.24 mm ~ 3.20 mm

Maximum deflection limit during load test of HCS 265:

$\Delta = L^2 / (20000h)$ = (10360 mm)2 / (20000 x 335 mm)

Δ = 16.02 mm ~ 16.00 mm

When actual maximum deflection is less than maximum deflection limit as stated above (i.e. 3.20 mm for HCS 150 and 16.00 mm for HCS 265), recovery is waived. Members failing to meet 75% recovery criterion may be retested. Before retesting, 72 hours must have elapsed after load removal. On retest, the recovery must be 80%. As per ACI 20.5.4, in regions of structural members without transverse reinforcement, appearance of structural cracks inclined to the longitudinal axis and having a horizontal projection longer than the depth of the member at midpoint of the crack shall be evaluated.

The deflection in both types of hollow core slabs were measured with three dial gauges with 0.01mm sensitivity located below the hollow core slabs. One at the middle and the other two at both ends. A visual inspection was carried out before pouring of concrete to check if there is presence of cracks at the top and bottom of the hollow core slabs and after the inspection it was verified that there were no cracks present. After the load setup has finished the Cycle 1 of loading sequence is followed.

3.5 Methodology followed for software analysis

Hollow core slabs are most analyzed as beams with simply supported condition on both ends. Most of the researchers use finite element analysis software like ANSYS for the analysis. But since hollow core slabs have complicated profiles and requires special details like openings and core fillings this software is not used for practical purposes. There are further hollow core software programs like PRE-Stress, dlubal, flooroffice, spiroll and floorcad which are used commercially.

In the United Arab Emirates though, Concise beam software which is developed by Canadian company BALCKMINT is predominantly used because of its versatility. The software has a very straightforward user interface and often the results are very conservative compared to other software programs.

3.5.1 Defining the beam

First step in the design is to define the beam in the program. Since ELEMATIC sections are already provided in the library we can select the hollow core slab as per the section thicknesses in our case 150mm and 265mm. The geometry of the hollow core slabs can be checked in the section properties tab to verify it is matching with the section we will be using. The span of the beam, bearing length, the presence of openings if any and beam handling parameters can be input in this section

3.5.2 Defining material properties

Concrete properties including the strength and transfer stage, lifting and final stage can be defined here. Material properties of cast in place pour or topping concrete can be input separately as it is often different to that of hollow core slab. Prestressing steel and reinforcing steel has to defined as per requirement. There are options of inputting whether the strand has been cut, fully bonded or de-bonded. Prestressing strand properties can be manually input or the available from the library can be used.

3.5.3Analysis of hollow core slabs

After further defining the design parameters the loads can be input. Loads can be input as uniformly distributed or point load as required. The stages of the loadings can also be input as suited. The self-weight of the hollow core slab can be cross verified as it is program generated and if there is any variation can be edited manually. After inputting all the parameters, the system can be run which will provide us the required results. Graphs and diagrams can be generated for flexure, shear, different stages of deflection, concrete stresses and so on. Detailed results showing the analysis and design can be generated further.

Chapter 4
Test Results and discussion

Readings from the three gauges below the hollow core slabs were recorded in at 0% loading, 25% loading, 50% loading, 75% loading, 100% loading, 100% sustained loading and 0% released load condition after 24 hours. Gauges were located at the center and near the end supports. Since the test was non-destructive test, the cracking patterns could not be observed. Both the hollow core slab load tests where only performed after the topping concrete was properly cured.

The results are as follows.

4.1 Load Test Results of HCS-150

Loading test results of HCS-150 can be tabulated as below

Loading Sequence	Deflection Readings (mm)		
	DG-01	DG-02	DG-03
Load 00%	0.00	0.00	0.00
Load 25%	0.01	0.01	0.01
Load 50%	0.02	0.02	0.02
Load 75%	0.03	0.03	0.03
Load 100%	0.05	0.05	0.05
Load 100% held for 24 Hours	0.16	0.29	0.19
Released Load 0%held for 24 Hours	0.06	0.11	0.09

Table 7 – HCS 150 Load test results

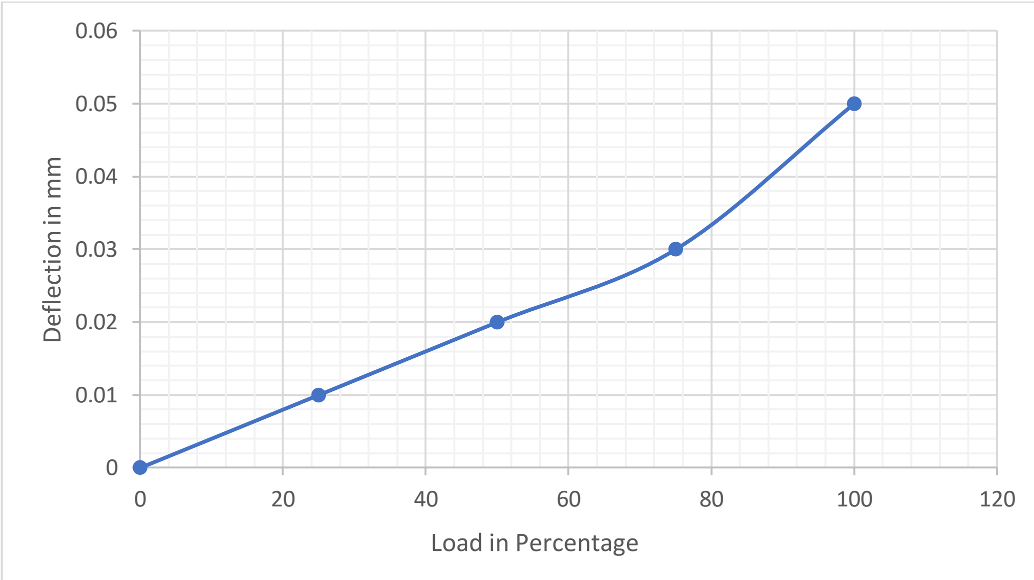

Figure 16 – Load v/s deflection graph for HCS 150

4.1.1 Result discussion for HCS-150

Hollow core slabs were measured at each stage and as we can see the deflections increased minimally during when the loadings were applied after one-hour gap. The two measuring gauges which should have been kept ideally near to the end supports were also kept near to the center due to which there is no much difference between readings of all the three gauges. Deflections increased by 0.01mm only in each of 25%, 50% and 75% loadings. But for 100% loadings, the deflection increased by 0.02mm. In sustained loading though there was a considerable increase in deflection. Deflection increased by 0.11mm and 0.14mm at left and right ends respectively whereas in the center the deflection increased by 0.24mm. After the measurement of the readings, the loadings were immediately released. The hollow core slab was under zero loading condition for 24 hours after which the deflection was measured again in which it was found that the final deflection was reduced to 0.06mm to the left, 0.09mm to the right and 0.11mm at the center. The residual deflection indicates the loss of elasticity in the hollow core slab.

The tested hollow core slab didn't show any sign of cracking and the measured final deflection is 0.29mm (middle gauge reading at 100% loading after 24 hours) which is way less than 3.2mm the maximum deflection limit as specified in the acceptance criteria. Since the maximum deflection is less than the maximum deflection limit recovery is waived. Hence it can be concluded that the hollow core slabs were within the acceptance criteria and the hollow core slabs are safer within the design loads.

During the entire testing process there was no major deflection noted and no cracks observed. Since the test setup is large, it is difficult to make destructive testing in this case. The considerable difference between the left and right gauges may be due to the presence of openings in the hollow core slabs which were provided to reflect the actual condition in the site. During all the loading stages composite action was observed and there was no debonding between the hollow core slabs and the topping even though there were no tie reinforcements from the hollow core slabs.

4.2 Load Test Results of HCS-265

Loading test results of HCS-265 can be tabulated as below

Loading Sequence	Deflection Readings (mm)		
	DG-01	DG-02	DG-03
Load 00%	0.00	0.00	0.00
Load 25%	-0.06	0.16	-0.05
Load 50%	0.35	0.60	0.45
Load 75%	0.75	1.36	0.74
Load 100%	1.18	2.02	1.15
Load 100% held for 24 Hours	2.06	3.36	1.98
Released Load 0%held for 24 Hours	-0.02	-0.08	-0.04

Table 8 – HCS 265 Load test results

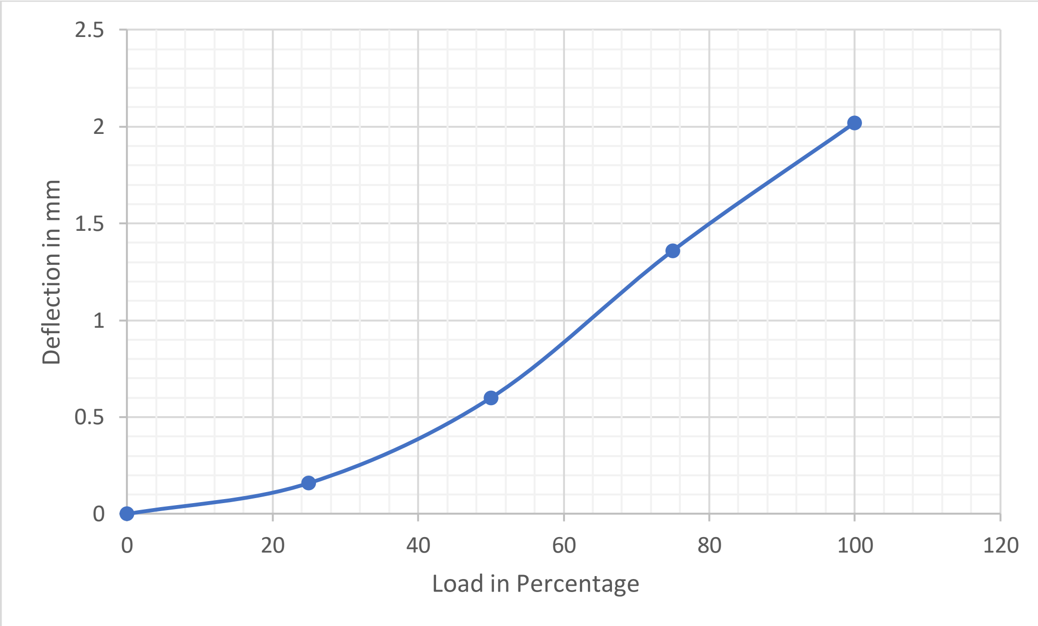

Figure 17 – Load v/s deflection graph for HCS 265

4.2.1 Result discussion for HCS-265

Similar to the testing of hollow core slab 150, the slabs were measured at each stage and as we can see the deflections increased more than that of HCS 150 when the loadings were applied after one-hour gap. In this case though, the end gauges were placed nearer to the supports due to which we can observe widely varied deflection in the end and center dial gauges.

In the initial stage of 25% loading, further increase in camber was observed in the end gauges due to which the deflection is shown in negative but in the central gauge the deflection was 0.16mm. At 50% loading there was considerable deflection in the end gauges also due to which the deflection was 0.35mm and 0.45 mm at the end gauges and the central gauge showed a deflection of 60mm. At 75% loading the deflection raised considerably and it read 0.75mm and 0.74mm at the ends and 1.36mm at the center. As the loading was increased to 100%, deflection increased but it didn't increase as steeply as it increase when the loading was increased from 50 % to 75%. The deflection read 1.18mm and 1.15mm at the ends and 2.02mm at the center. Deflection was found to be the maximum when the reading was taken after 24 hours of sustained 100% loading which was 2.06mm and 1.98mm at the ends and 3.36mm at the center. When the loadings were released and the deflections were measured after 24 hours it was observed the beam showed camber. The end readings -0.02mm and -0.04mm while the central reading was -0.08mm. This shows that the beam setup retained its elasticity even after sustained loading and the composite action was completely intact.

The tested hollow core slab didn't show any sign of cracking and the measured final deflection is 3.36mm (middle gauge reading at 100% loading after 24 hours) which is less than 16.0mm. Since the maximum deflection is less than the maximum deflection limit recovery is waived. Hence it can be concluded that the hollow core slabs were within the acceptance criteria and the hollow core slabs are safer within the design loads. There were no signs of cracks in the interface of hollow core slab and the structural screed and there was no visible debonding even without interface studs or bonding agents.

4.3 Comparison with previous researches

All of the previous researches we had discussed in the literature review considered only individual slabs and the load setup were on much smaller scale. Since this test setup was on a higher scale and three hollow core slabs were acting together as a single unit, the deflection of the hollow core slabs with topping was much lesser and less significant when compared to earlier researches.

Chapter 5
Composite and non-composite HCS software analysis

5.1 Analysis and design of hollow core slabs with concise beam software

Hollow core slabs 150mm and 265mm thick are both analyzed in Concise beam software. Both are analyzed first as composite and secondly as non – composite and will be cross checked with the actual results.

In the software analysis we will first see the hollow core slab diagram, the analysis and then the detailed analysis results. From the detailed analysis results the deflection can be found which can be verified with the actual results.

5.1.1. Hollow core slab 150 considered as composite

In this case the hollow core slab will be analyzed considering as composite with topping of 65mm. Only single hollow core slab can be analyzed using the Concise beam software. The analyzed beam will be as follows.

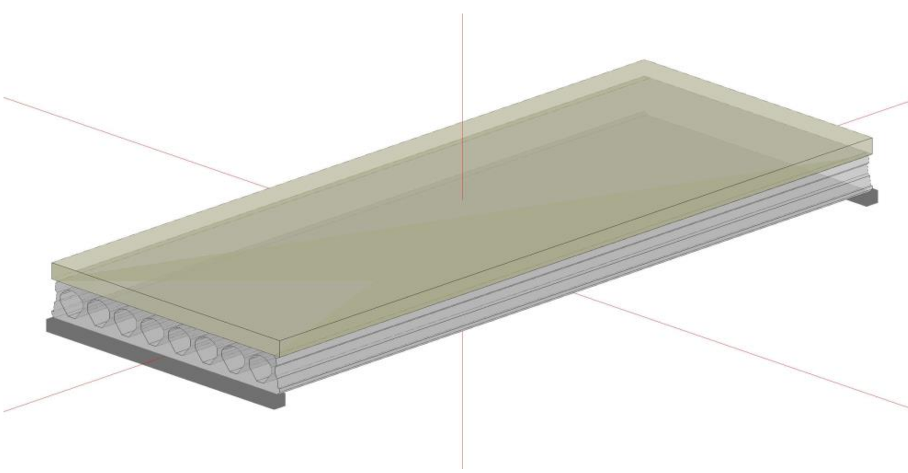

Figure 18 - HCS 150 Composite section

We will be reviewing the flexure, shear, deflections and concrete stresses in the hollow core slabs.

The flexure diagram is as follows

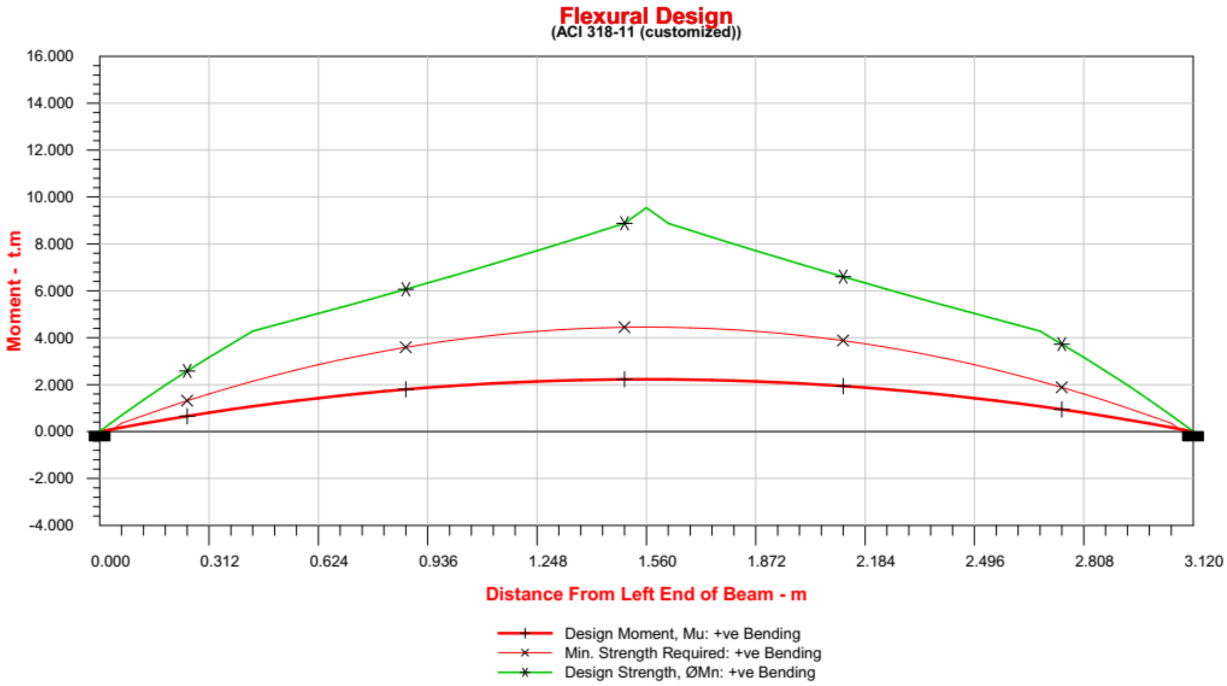

Figure 19 - HCS 150 Composite section flexure diagram

Maximum design moment is at the center which 2.23 t.m (21.9 KNm) whereas the minimum strength required as per ACI 318-11 at this point is 4.45 t.m (43.8 KNm). The design strength provided is 9.54t.m (93.56 KNm) which is well above these values and hence the beam is considered safe for flexure. As the beam is considered as simply supported, we can see that the moments become zero at the supports. As found in the literature review flexure is the more critical than shear in smaller depth hollow core slabs like 150mm.

Shear capacity of the hollow core slab was also found to be well within required capacity. Shear requirement was maximum at both the supports which was 25.53 KN. Even though the maximum shear strength of 66.50 KN was not at the support the value of 29.88 KN which was the support shear strength was above the required. The shear diagram was as below.

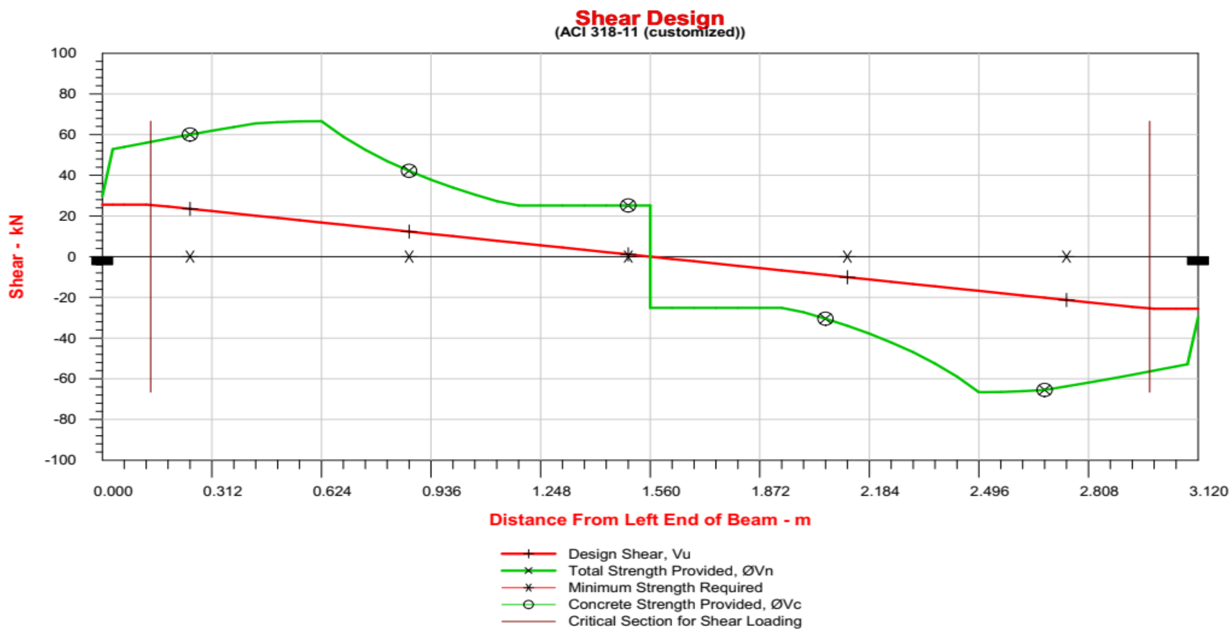

Figure 20 - HCS 150 Composite section shear diagram

The main parameter which the test is based on is the deflection. The deflection diagrams are as below.

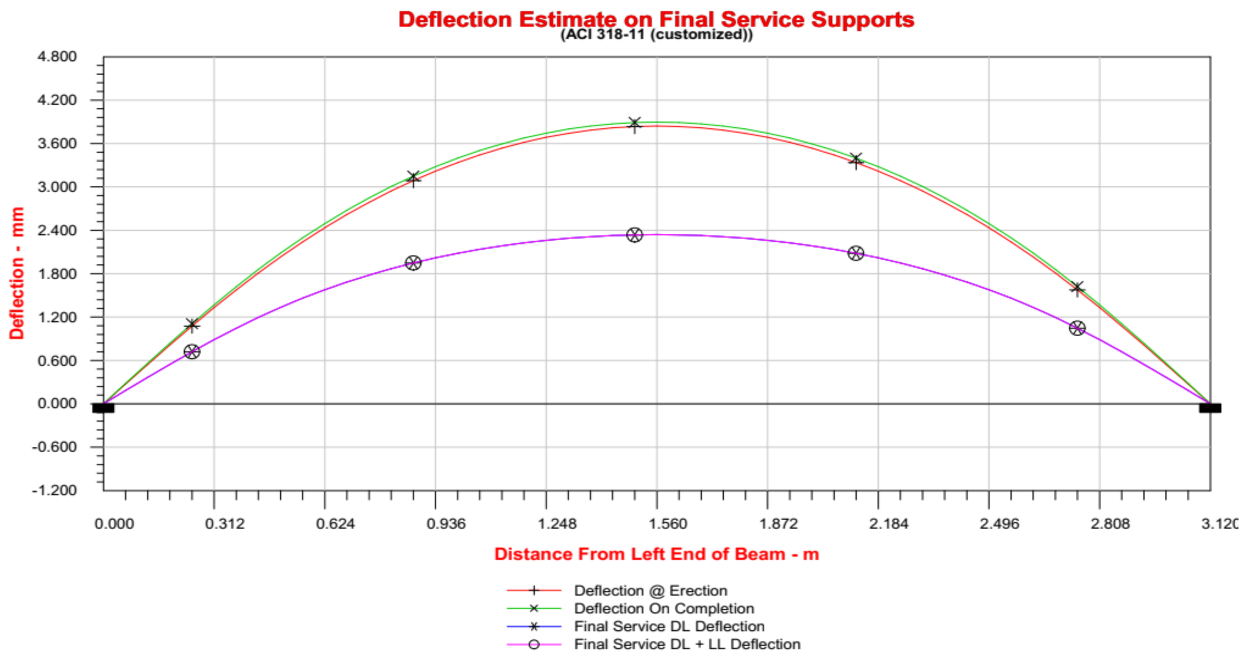

Figure 21 - HCS 150 Composite section deflection estimate on final service support

Deflection on the hollow core slab is estimated to be 3.9mm at completion. Due to prestressing, there is camber in the hollow core slab which is indicated as positive. After the load completion the deflection is estimated to be 2.3mm which is still camber. The difference in camber is 1.6mm which should be checked with the measured gauge reading at the center at 100% loading.

Below graph shows the stresses in the beam during service condition.

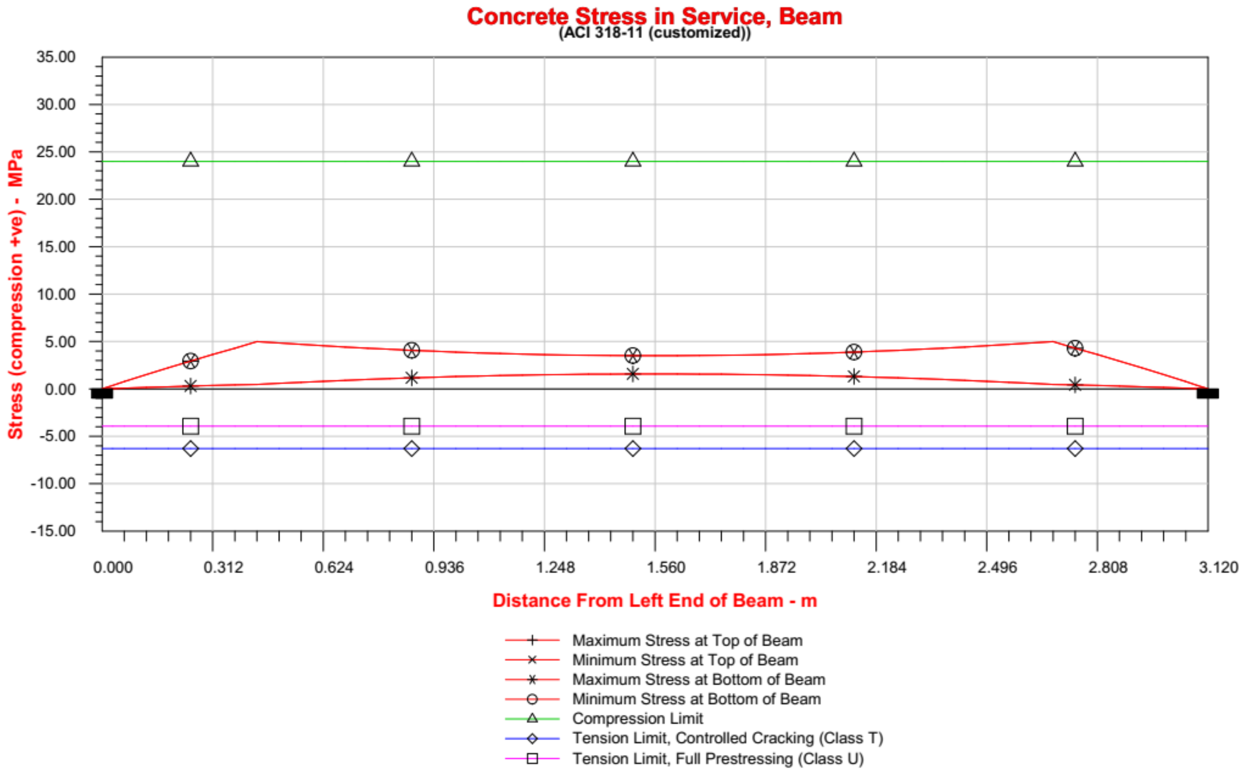

Figure 22 - HCS 150 Composite section concrete stress in service

Compression stress limit is 24 MPa and the tension stress limit is -6.3 MPa. Hollow core slab stays within the limit throughout the span which indicates there is no crack estimated in the analysis.

5.1.2. Hollow core slab 150 considered not as composite

In this case the hollow core slab will be analyzed considering as non-composite with topping of 65mm. The topping is considered as additional load only. The analyzed beam will be as follows.

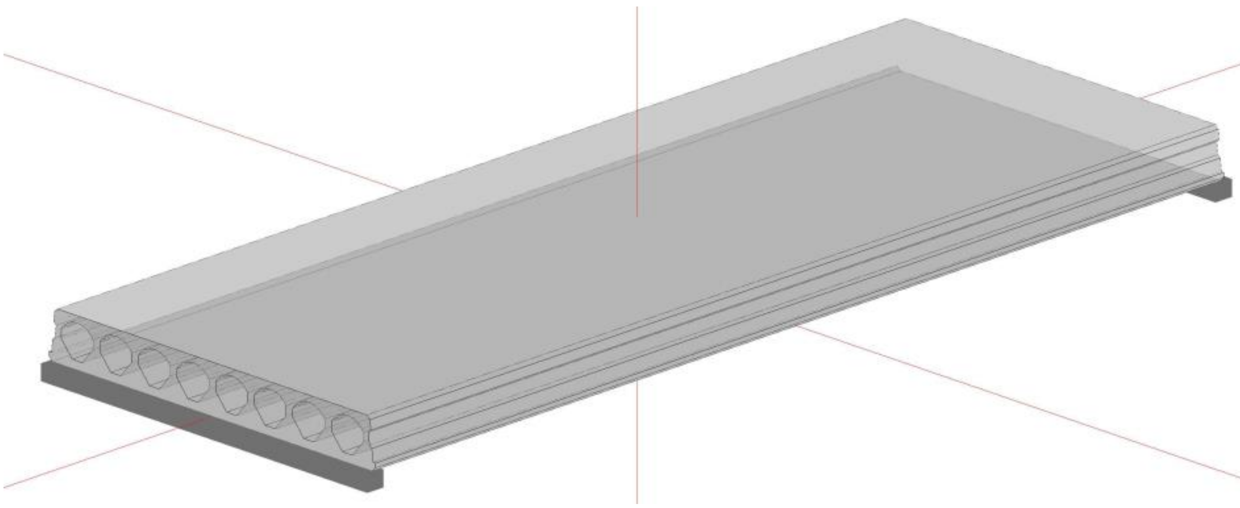

Figure 23 - HCS 150 non-composite section

We will be reviewing the flexure, shear, deflections and concrete stresses in the hollow core slabs.

The flexure diagram is as follows

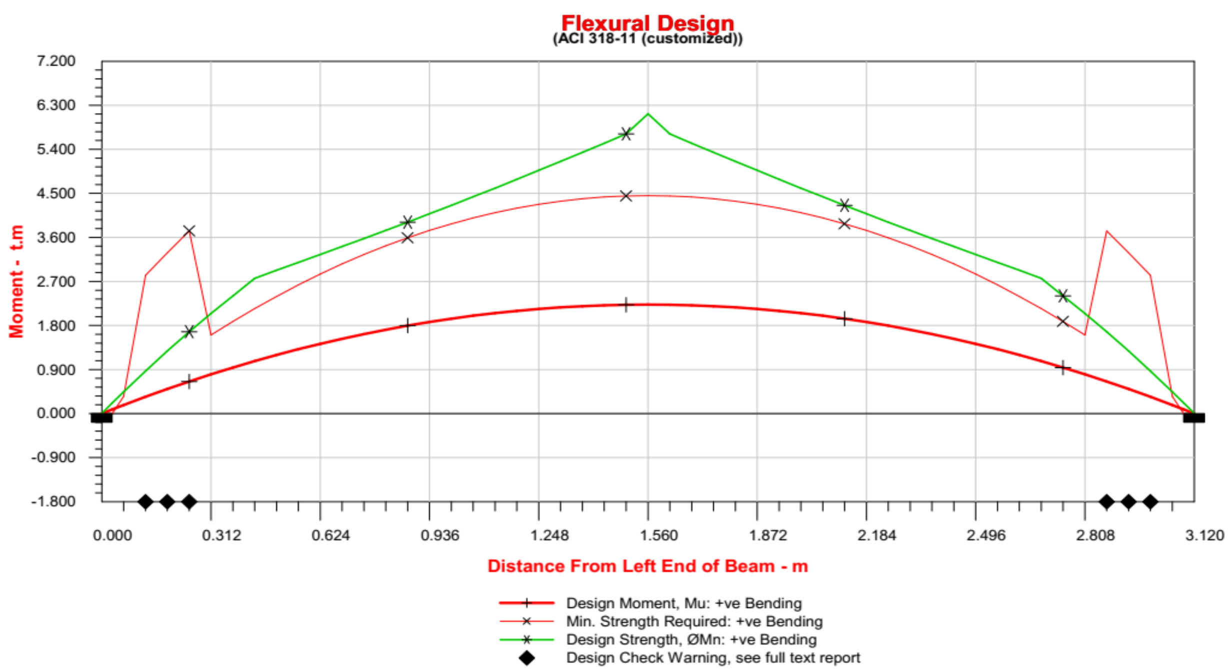

Figure 24 - HCS 150 non-composite section flexure diagram

Maximum design moment is at the center which 2.23 t.m (21.8 KNm) whereas the minimum strength required as per ACI 318-11 at this point is 4.45 t.m (43.7 KNm). The design strength provided is 5.71t.m which is above these values. At 0.25m the minimum required design strength is 3.73t.m (36.6 KNm) whereas the provided strength is 1.67 t.m (16.4 KNm) which is well below the required. If we consider the hollow core slab as non-composite it will fail under flexure.

Shear capacity of the hollow core slab was also found to be well within required capacity. Shear requirement was maximum at both the supports which was 26.12 KN. Even though the maximum shear strength of 45.98 KN was not at the support the value of 27.04 KN which was the support shear strength was above the required. The shear diagram was as below.

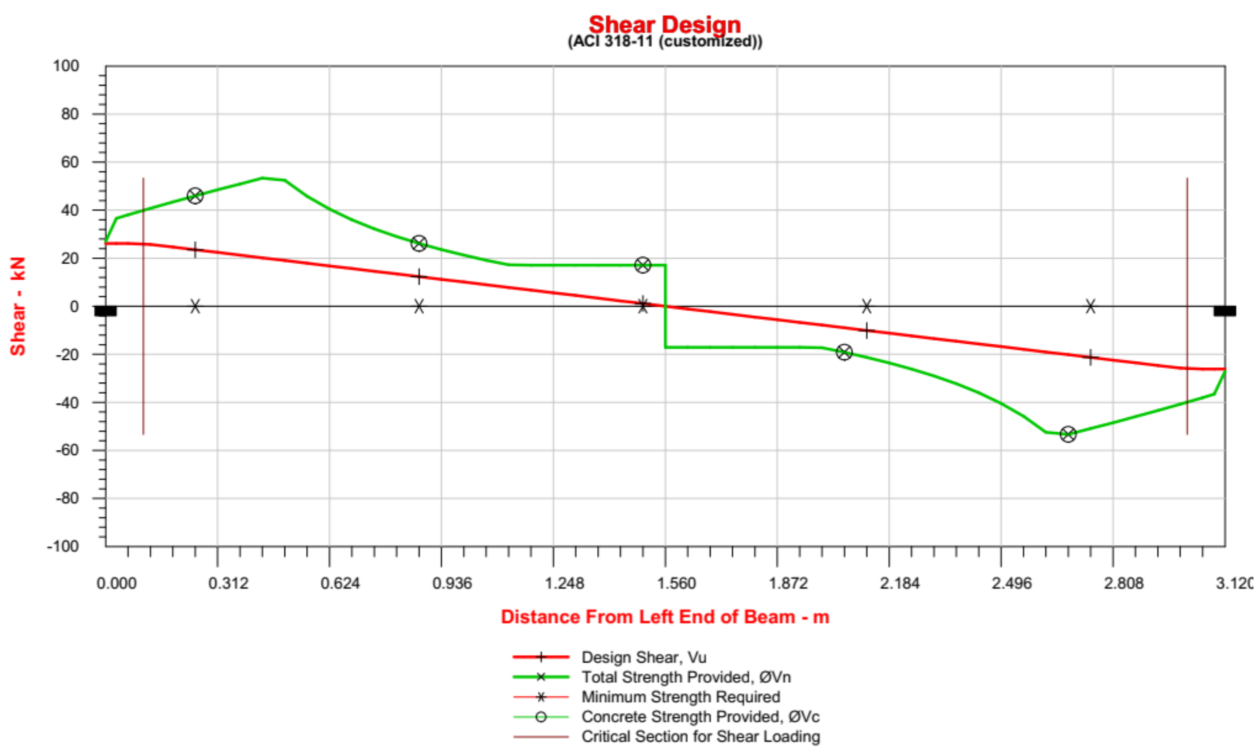

Figure 25 - HCS 150 non-composite section shear diagram

The main parameter which the test is based on is the deflection. The deflection diagram is as below.

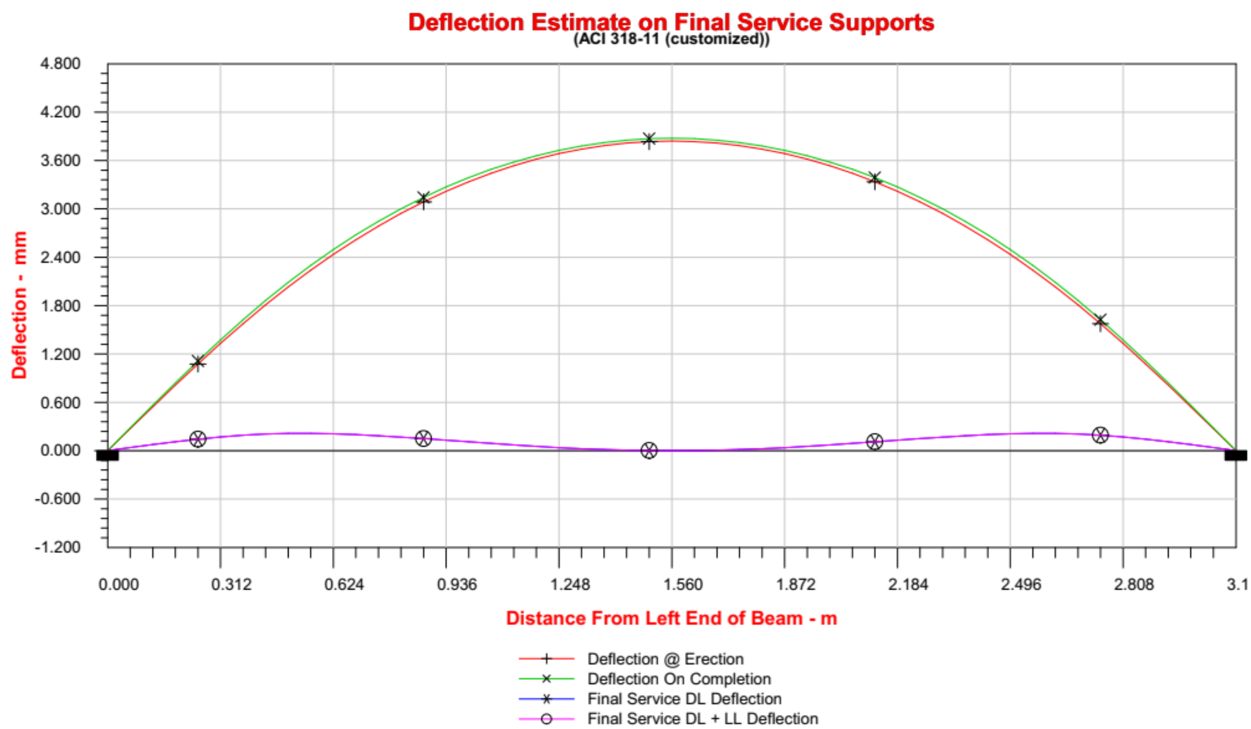

Figure 26 - HCS 150 non-composite section deflection estimate on final service support

We can immediately observe that there is a major variation in the deflection of composite and non-composite section. In the first case there was only camber observed whereas in non-composite section we can observe that at center there is zero deflection. Similar to the composite condition, deflection on the hollow core slab is estimated to be 3.9mm at completion. After the load completion the deflection is estimated to be 0mm. The difference in camber is 3.9mm which should be checked with the measured gauge reading at the center at 100% loading.

Compression stress limit is 24 MPa and the tension stress limit is -6.3 MPa. Hollow core slab stays within the limit throughout the span which indicates there is no crack estimated in the analysis.

Below graph shows the stresses in the beam during service condition.

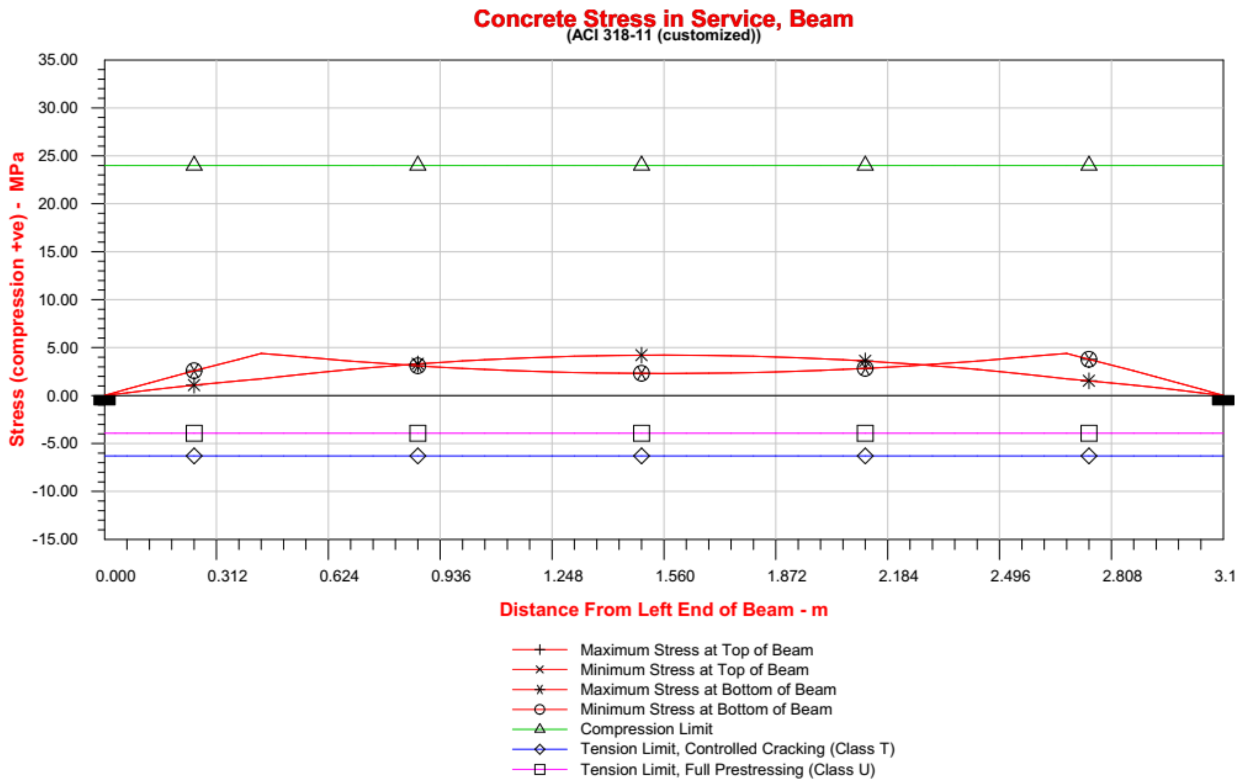

Figure 27 - HCS 150 non-composite section concrete stress in service

Following the analysis, we can observe that the element is not safe under flexure and if we are to consider con-composite section, the section should be modified to meet desired flexural capacity.

5.1.3. Hollow core slab 265 considered as composite

In this case the hollow core slab will be analyzed considering as composite with topping of 70mm. Only single hollow core slab can be analyzed using the Concise beam software. The analyzed beam will be as follows.

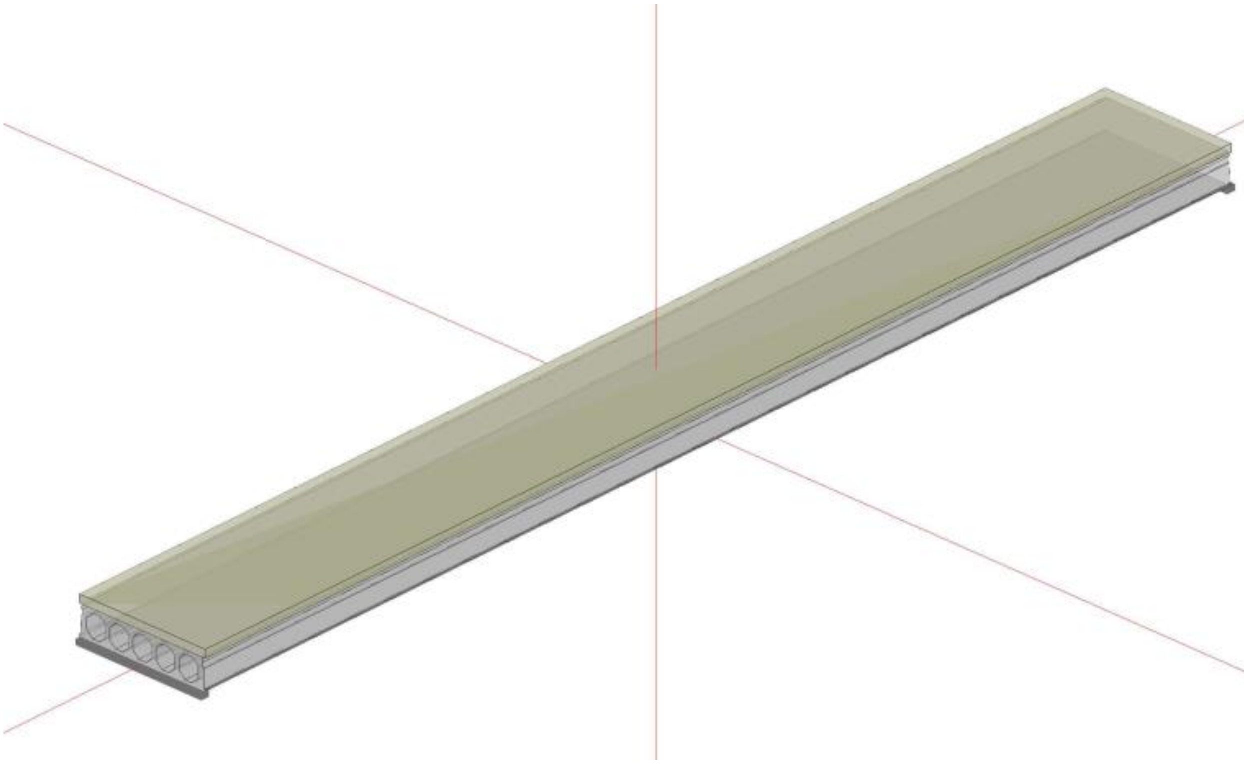

Figure 28 - HCS 265 Composite section

We will be reviewing the flexure, shear, deflections and concrete stresses in the hollow core slabs.

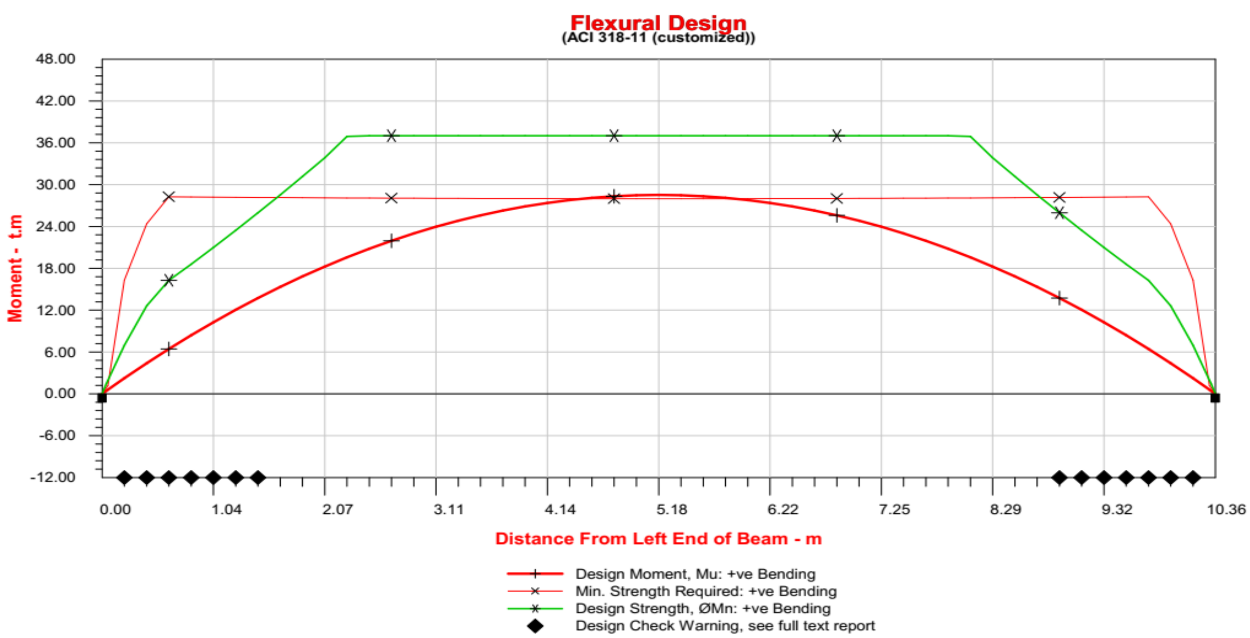

Figure 29 - HCS 265 Composite section flexure diagram

Maximum design moment is at the center which 28.52 t.m (279.7 KNm) whereas the minimum strength required as per ACI 318-11 at this point is 27.99 t.m (274.5 KNm). The design strength provided is 37.02t.m (363 KNm) which is above these values. At 0.622m the minimum required design strength is 28.26t.m (277.14 KNm) whereas the provided strength is 16.27 t.m (160 KNm) which is less than required.

Shear capacity of the hollow core slab was also found to be just outside required capacity. Shear requirement was maximum at both the supports which was 103.68 KN. The maximum shear strength of 138.11 KN was not at the support and the value of 95.29 KN which was the support shear strength was just below the required. The required shear capacity can be achieved filling cores in the support area. The shear diagram was as below.

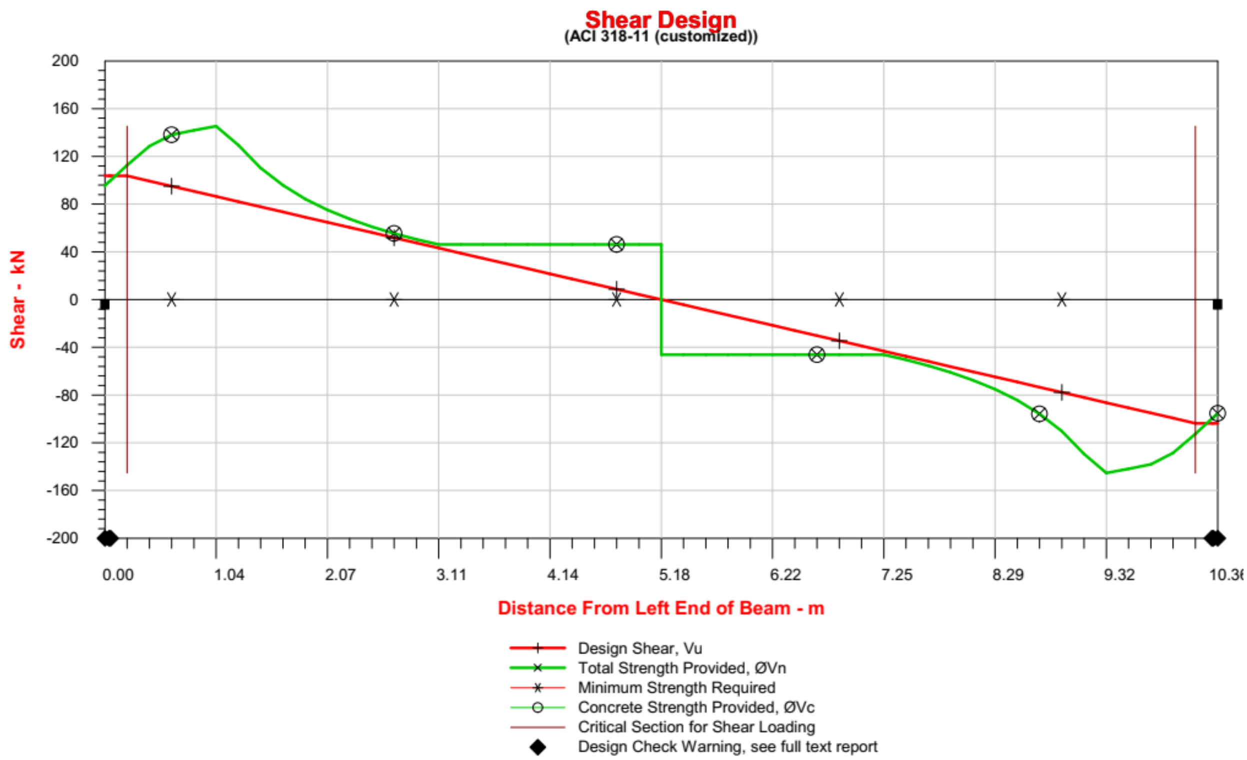

Figure 30 - HCS 265 Composite section shear diagram

The main parameter which the test is based on is the deflection. The deflection diagrams are as below.

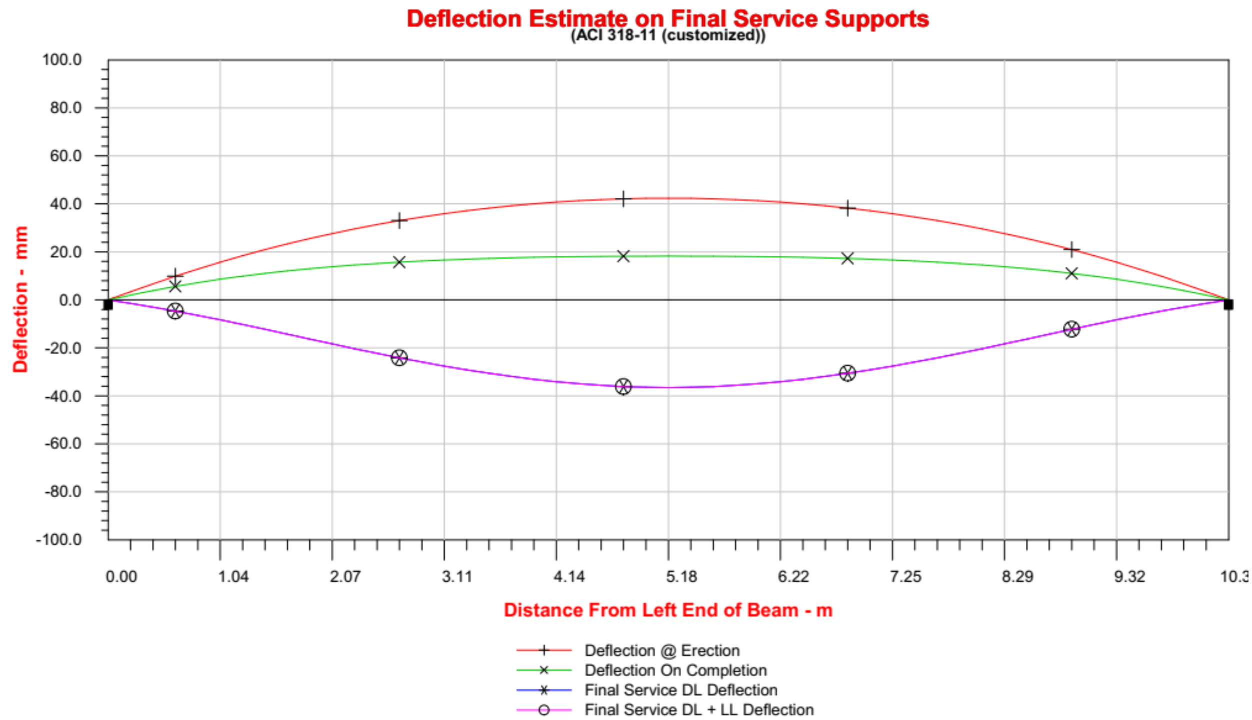

Figure 31 - HCS 265 Composite section deflection estimate on final service support

Deflection on the hollow core slab is estimated to be 18.2mm at completion. Due to prestressing, there is camber in the hollow core slab which is indicated as positive. After the load completion the deflection is estimated to be 36.1mm which is shown as downward deflection. The difference in camber is 54.3mm which should be checked with the measured gauge reading at the center at 100% loading.

Compression stress limit is 24 MPa and the tension stress limit is -6.3 MPa. Hollow core slab stress exceeds the tension stress limit the center of the span. As per the estimated analysis there should be controlled cracking at the center of the hollow core slabs.

Below graph shows the stresses in the beam during service condition.

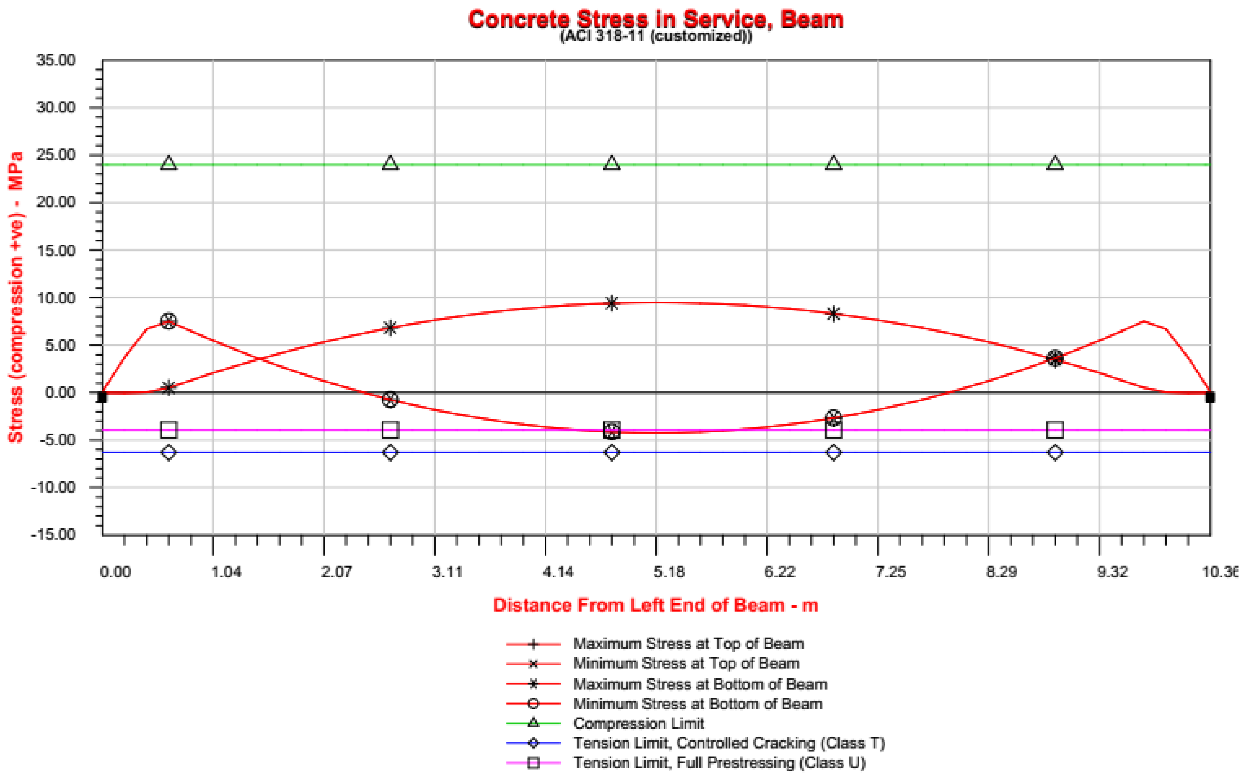

Figure 32 - HCS 265 Composite section concrete stress in service

5.1.4. Hollow core slab 265 considered as non-composite

In this case the hollow core slab will be analyzed considering as non-composite with topping of 70mm. Only single hollow core slab can be analyzed using the Concise beam software. The analyzed beam will be as follows.

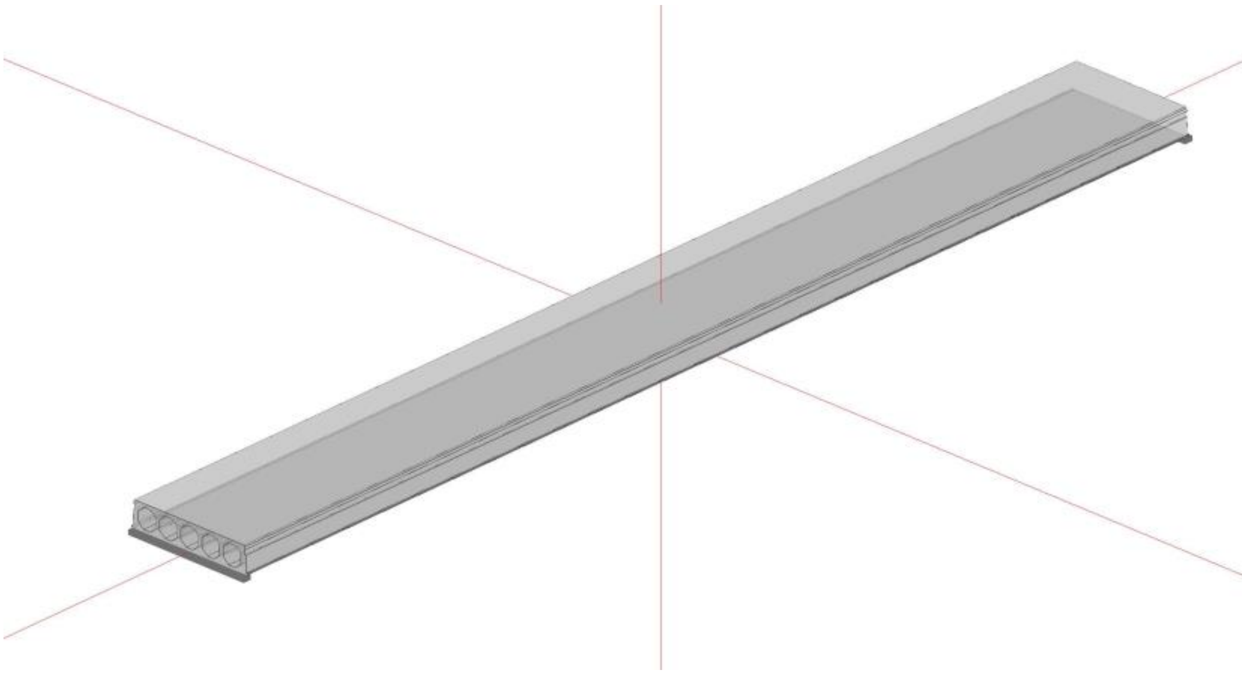

Figure 33 - HCS 265 non-composite section

We will be reviewing the flexure, shear, deflections and concrete stresses in the hollow core slabs.

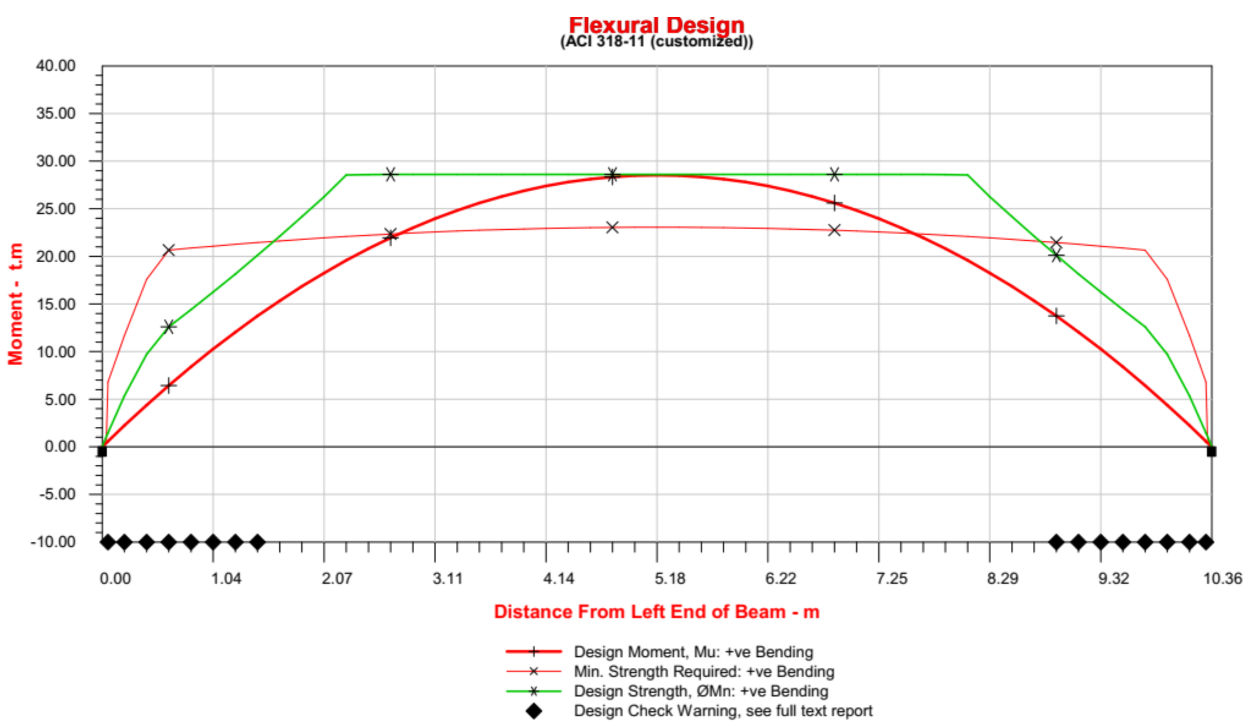

Figure 34 - HCS 265 non-composite section flexure diagram

Maximum design moment is at the center which 28.52 t.m (279.7 KNm) whereas the minimum strength required as per ACI 318-11 at this point is 23.06 t.m (226.14 KNm). The design strength provided is 28.6t.m (280.47 KNm) which is above these values. At 0.622m the minimum required design strength is 20.65t.m (202.5 KNm) whereas the provided strength is 12.6 t.m (123.56 KNm) which is below the required.

Shear capacity of the hollow core slab was also found to be outside required capacity. Shear requirement was maximum at both the supports which was 104.41 KN. The maximum shear strength of 134.49 KN was not at the support and the value of 75.88 KN which was the support shear strength was just below the required. In this case the shear case falls below the required capacity not only at the supports as can be visualized in the below diagram. Hence this beam can be considered as failed under design load as per the analysis.

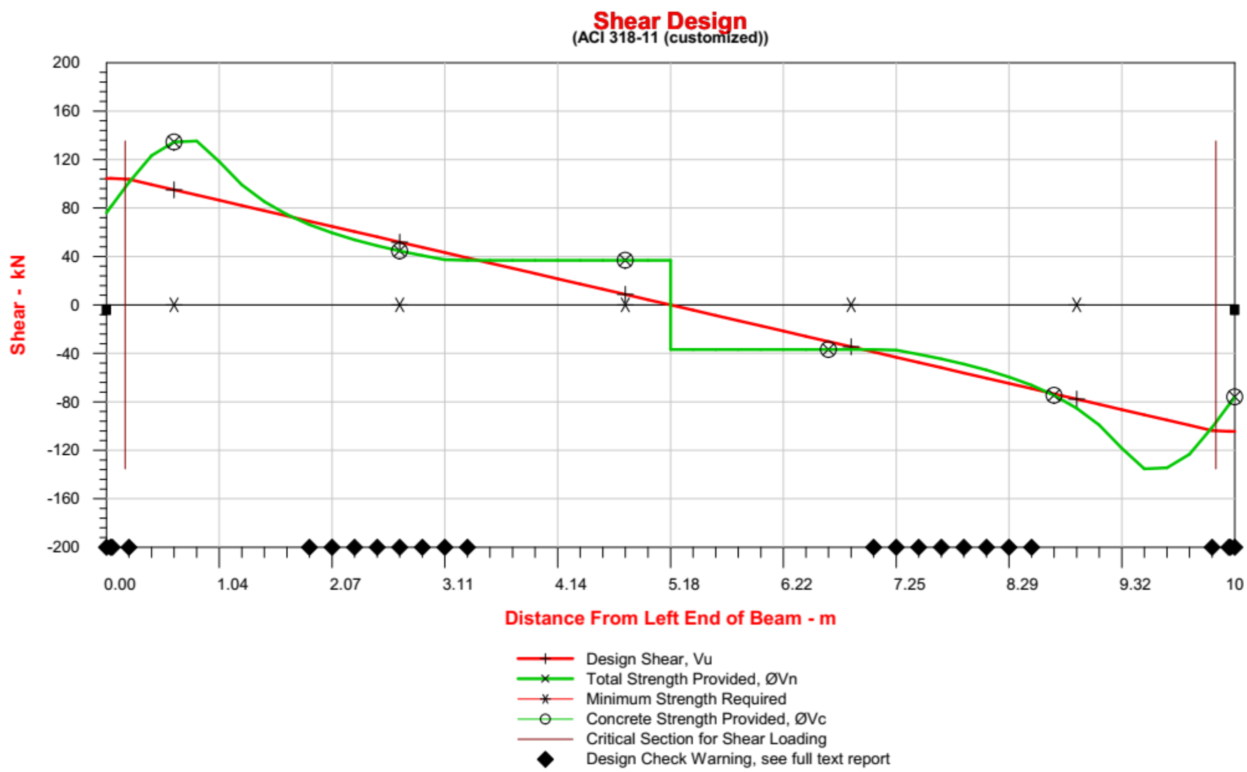

Figure 35 - HCS 265 non-composite section shear diagram

The main parameter which the test is based on is the deflection. The deflection diagrams are as below.

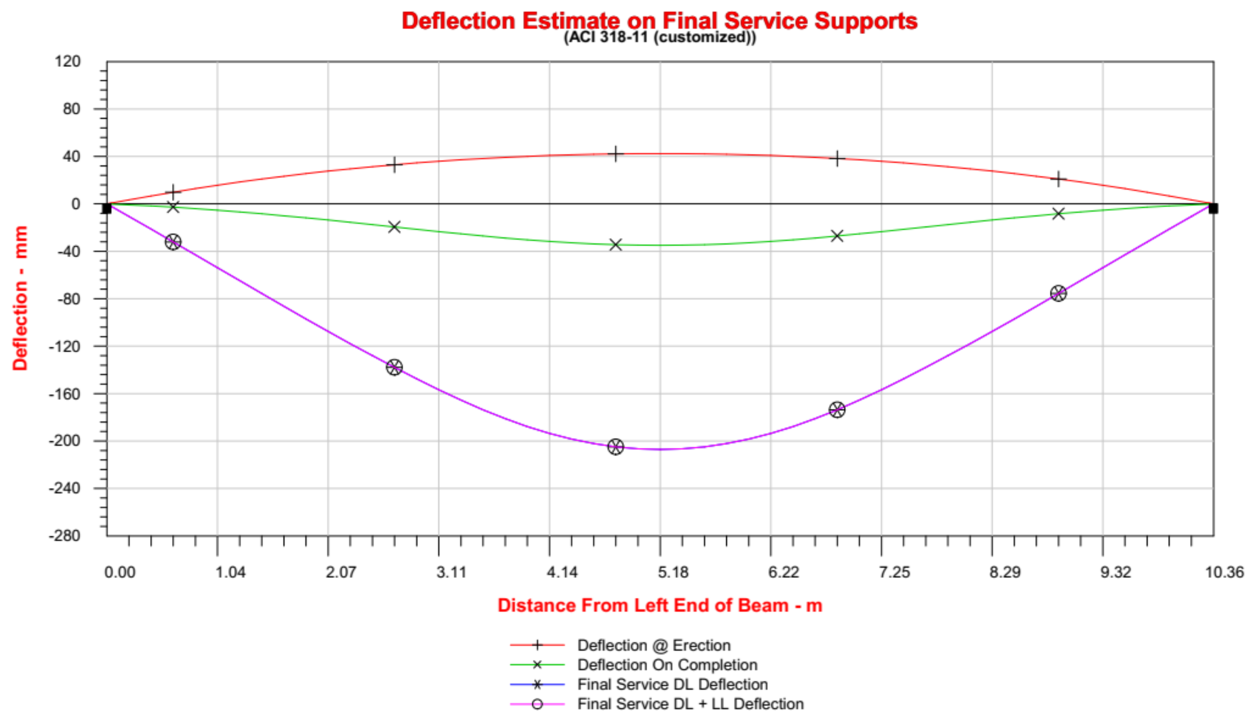

Figure 36 - HCS 265 non-composite section deflection estimate on final service support

Deflection on the hollow core slab is estimated to be 35mm after topping is poured. After the load completion the deflection is estimated to be 207.2mm which is way too higher. The difference is 172.2mm which should be checked with the measured gauge reading at the center at 100% loading.

Compression stress limit is 24 MPa and the tension stress limit is -6.3 MPa. Hollow core slab stress exceeds the tension stress limit the center of the span. As per the estimated analysis there should be cracking at the center of the hollow core slabs.

Below graph shows the stresses in the beam during service condition.

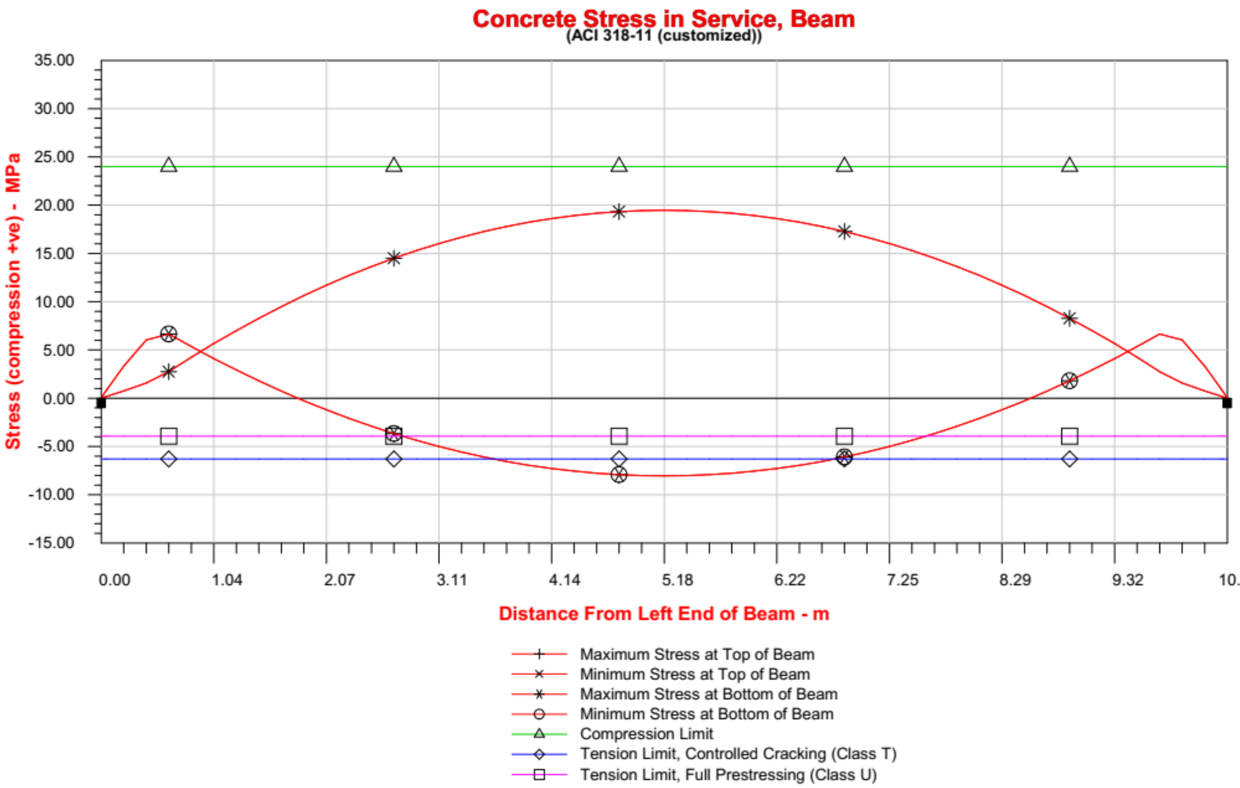

Figure 37 - HCS 265 Composite section concrete stress in service

5.2 Comparison of the analysis data with the actual results

For HCS-150 considered as composite in the analysis the estimated deflection is 1.6mm and for HCS-150 considered as non- composite in the analysis the estimated deflection is 3.9mm. From the actual test setup, we have already seen that the deflection is 0.29mm which is way less than both the values.

For HCS-265 considered as composite in the analysis the estimated deflection is 54.8mm and for HCS-265 considered as non- composite in the analysis the estimated deflection is 172.2mm. From the actual test setup, we have already seen that the deflection is 3.36mm which is way less than both the values.

It is safe to assume from both HCS-150 and HCS-265 that since the estimated deflection even from the composite sections are way more than the actual deflection, non-composite sections can be ignored.

5.3 Variation in the actual and analyzed deflection values

The huge variation in the analyzed and actual deflection values are due to a number of reasons. In the analysis stage only one hollow core slab is considered but in the test condition the load is distributed between three hollow core slabs and the resulting load on the central hollow core slab is lesser. Design parameters input in the analysis will not be followed the same way during production. There is safety factor in parameters like the capacity of prestressing strand and the compressive strength of concrete in topping and hollow core slabs which are always more than that considered.

Chapter 6
Conclusion and recommendations

6.1 Conclusion and recommendations

This research aimed at the comparing the analysis of composite action of precast hollow core slabs and cast in place mesh reinforced concrete topping and actual composite action at the site. It can be concluded that

- when adequate roughness in maintained at the top of the factory cast hollow core slabs and in uncracked condition the composite action is applicable and the test results which simulates the actual site conditions are well within the safe limit and the values obtained through the analysis software Concise beam. Composite action was observed throughout the test and there were no cracks in the interface and there was no debonding between the topping and the hollow core slabs
- No special connections are required to attain composite action of hollow core slabs. Roughness formed during machine cast in the top of hollow core slab was enough.
- The software analysis by Concise beam provides very conservative design and, in some cases, where the software analysis indicated cracks in the slab, there were no cracks to be observed.
- Ideal setup of load testing in hollow core slab should be matching the site situation in which the hollow core slabs are arranged side by side before pouring of the topping.

The test setup was reflective of the actual site conditions with the connections, the supports and the loadings. Readings were taken before loading, during the sequence of incremental loadings, after 24 hours of loading and even after the loadings were released to satisfy the acceptance criteria set upon by ACI 318M-11. The tests were done under third party inspection also so that there may not be any ambiguity. The objective of this research was to establish that the topping can be considered with hollow core slab as a single structural composite element for all practical purposes even without steel anchors and this has been validated.

As already pointed out in the literature review it was found that the composite action was valid in all the hollow core slabs during the test stages. It should also be noted that the tests were conducted only in the uncracked condition as assumed early on and also as considered during the analysis stage.

6.2 Recommendations

The investigations conducted in this research was only limited to hollow core slabs of ELEMATIC sections with 150mm and 265mm thicknesses. The prestressing strands were stressed up to 60% only as per the standard practice and all the elements were in uncracked condition throughout the test period. Further investigations should be conducted for other sections of hollow core slabs and through different levels of prestressing. Hollow core slabs should also be checked in cracked condition to review the worst-case scenario. This research could establish that for hollow core slabs of 150mm and 265mm thick with the prestressing as mentioned above and under the circumstances as established in test setup could show composite behavior with the structural screed. Since the deflection in the test setup were almost ten times lesser than the calculated deflections, its composite action can be safely assumed.

References

1. A. Youssef, M. & Aiham, A. (2013). Composite Behaviour of Hollowcore Slabs and Cast-in-Situ Concrete Topping. *PCI/NBC*.
2. Adawi, A., Youssef, M. A. & Meshaly, M. E. (2015). Experimental investigation of the composite action between hollowcore slabs with machine-cast finish and concrete topping. *Engineering Structures*. Elsevier Ltd, vol. 91, pp. 1–15.
3. Adawi, A., Youssef, M. A. & Meshaly, M. E. (2016). Evaluating interfacial shear stresses in composite hollowcore slabs using analytical solution. *Alexandria Engineering Journal*. Faculty of Engineering, Alexandria University, vol. 55(3), pp. 2647–2654.
4. Aguado, J. V., Espinos, A., Hospitaler, A., Ortega, J. & Romero, M. L. (2012). Influence of reinforcement arrangement in flexural fire behavior of hollow core slabs. *Fire Safety Journal*, vol. 53, pp. 72–84.
5. Al-Azzawi, A. A. & Abdul Al-Aziz, B. M. (2018). Behavior of reinforced lightweight aggregate concrete hollow-core slabs. *Computers and Concrete*, vol. 21(2), pp. 117–126.
6. Al-Azzawi, A. A. & Abed, S. A. (2017). Investigation of the behavior of reinforced concrete hollow-core thick slabs. *Computers and Concrete*, vol. 19(5), pp. 567–577.
7. Al-Negheimish, A. I., El-Sayed, A. K., Khanbari, M. O. & Alhozaimy, A. M. (2018). Long-term deflection of prestressed SCC hollow core slabs. *Construction and Building Materials*. Elsevier Ltd, vol. 189, pp. 181–191.
8. Al-Shaarbaf, I. A., Al-Azzawi, A. A. & Abdulsattar, R. (2018). A state of the art review on hollow core slabs. *ARPN Journal of Engineering and Applied Sciences*, vol. 13(9), pp. 3240–3245.
9. Albero, V., Saura, H., Hospitaler, A., Montalvà, J. M. & Romero, M. L. (2018). Optimal design of prestressed concrete hollow core slabs taking into account its fire resistance. *Advances in Engineering Software*. Elsevier, vol. 122(April), pp. 81–92.
10. Baldassino, N., Roverso, G., Ranzi, G. & Zandonini, R. (2019). Service and Ultimate Behaviour of Slim Floor Beams: An Experimental Study. *Structures*. Elsevier, vol. 17(September 2018), pp. 74–86.
11. Baran, E. (2015). Effects of cast-in-place concrete topping on flexural response of precast concrete hollow-core slabs. *Engineering Structures*. Elsevier Ltd, vol. 98, pp. 109–117.
12. Becker, R. J. & Buettner, D. R. (1985). Shear Tests of Extruded Hollow-Core Slabs. *Journal - Prestressed Concrete Institute*, vol. 30(2), pp. 40–54.
13. Bernardi, P., Cerioni, R., Leurini, F. & Michelini, E. (2016). A design method for the prediction of load distribution in hollow-core floors. *Engineering Structures*. Elsevier Ltd, vol. 123, pp. 473–481.
14. Brunesi, E., Bolognini, D. & Nascimbene, R. (2015). Evaluation of the shear capacity of precast-prestressed hollow core slabs: numerical and experimental comparisons. *Materials and Structures/Materiaux et Constructions*, vol. 48(5), pp. 1503–1521.
15. Cavaco, E. & Camara, J. (2017). Experimental research on the behaviour of concrete-to-concrete interfaces subjected to a combination of shear and bending moment. *Engineering Structures*. Elsevier Ltd, vol. 132, pp. 278–287.
16. Chang, J. J., Moss, P. J., Dhakal, R. P. & Buchanan, A. H. (2010). Effect of aspect ratio on fire resistance of hollow core concrete floors. *Fire Technology*, vol. 46(1), pp. 201–216.
17. Cho, K., Shin, Y. su & Kim, T. (2017). Effects of half-precast concrete slab system on construction productivity. *Sustainability (Switzerland)*, vol. 9(7).

18. Cuenca, E. & Serna, P. (2013). Failure modes and shear design of prestressed hollow core slabs made of fiber-reinforced concrete. *Composites Part B: Engineering*. Elsevier Ltd, vol. 45(1), pp. 952–964.
19. Daniel Ronald Joseph, J., Prabakar, J. & Alagusundaramoorthy, P. (2017). Precast concrete sandwich one-way slabs under flexural loading. *Engineering Structures*. Elsevier Ltd, vol. 138, pp. 447–457.
20. Derkowski, W. I. T. & Surma, M. (2015). Composite action of precast hollow core slabs with structural topping. *Technical Transactions*, (Civil Engineering Issue 3-B (23) 2015), pp. 15–29.
21. El-Sayed, A. K., Al-Negheimish, A. I. & Alhozaimy, A. M. (2019). Web shear resistance of prestressed precast deep hollow core slabs. *ACI Structural Journal*, vol. 116(1), pp. 139–150.
22. Fam, A. & Skutezky, T. (2006). Composite T-beams using reduced-scale rectangular FRP tubes and concrete slabs. *Journal of Composites for Construction*, vol. 10(2), pp. 172–181.
23. Frăţilă, E. & Kiss, Z. (2016). Finite Element Analysis of Hollow-Core Slabs. *Journal of Applied Engineering Sciences*, vol. 6(1), pp. 29–33.
24. Gadri, K. & Guettala, A. (2017). Evaluation of bond strength between sand concrete as new repair material and ordinary concrete substrate (The surface roughness effect). *Construction and Building Materials*. Elsevier Ltd, vol. 157, pp. 1133–1144.
25. Gravit, M., Nedviga, E., Vinogradova, N. & Teplova, Z. (2017). Fire resistance of prefabricated monolithic slab. *MATEC Web of Conferences*, vol. 106, pp. 1–8.
26. Haruna, S. I., Gora, A. M. & Malami, S. I. (2018). Geometric Impact on the Behaviour of Composite Precast Prestressed Concrete Hollow Core Slab, vol. 4(1), pp. 1–11.
27. Heiza, K. M., Elkholy, A. & Meleka, N. (n.d.). Performance of pphc bridge slabs with openings.
28. Hertz, K., Giuliani, L. & Sørensen, L. S. (2017). Fire resistance of extruded hollow-core slabs. *Journal of Structural Fire Engineering*, vol. 8(3), pp. 324–336.
29. Hosny, A., Sayed-Ahmed, E. Y., Abdelrahman, A. A. & Alhlaby, N. A. (2006). Strengthening precast-prestressed hollow core slabs to resist negative moments using carbon fibre reinforced polymer strips: An experimental investigation and a critical review of Canadian Standards Association S806-02. *Canadian Journal of Civil Engineering*, vol. 33(8), pp. 955–967.
30. Hsu, C. T. T., Punurai, S., Punurai, W. & Majdi, Y. (2014). New composite beams having cold-formed steel joists and concrete slab. *Engineering Structures*. Elsevier Ltd, vol. 71, pp. 187–200.
31. Ibrahim, I. S., Elliott, K. S., Abdullah, R., Kueh, A. B. H. & Sarbini, N. N. (2016). Experimental study on the shear behaviour of precast concrete hollow core slabs with concrete topping. *Engineering Structures*. Elsevier Ltd, vol. 125, pp. 80–90.
32. Jendzelovsky, N. & Zabakova Vrablova, K. (2015). Comparison of Natural Frequencies of Hollow Core Slabs. *Applied Mechanics and Materials*, vol. 769, pp. 225–228.
33. Kankeri, P., Chellapandian, M. & Prakash, S. S. (2017). Bonded overlay strengthening of hollow core slab with and without interface shear keys connection. *3rd International Symposium on Connections between Steel and Concrete . Stuttgart, Germany*.
34. Kankeri, P. & Suriya Prakash, S. (2017). Efficient hybrid strengthening for precast hollow core slabs at low and high shear span to depth ratios. *Composite Structures*.

Elsevier Ltd, vol. 170, pp. 202–214.
35. Kankeri, P., Suriya Prakash, S. & Pachalla, S. K. S. (2018). Analytical and numerical studies on hollow core slabs strengthened with hybrid FRP and overlay techniques. *Structural Engineering and Mechanics*, vol. 65(5), pp. 535–546.
36. Khalaf, J. & Huang, Z. (2016). Analysis of the bond behaviour between prestressed strands and concrete in fire. *Construction and Building Materials*. Elsevier Ltd, vol. 128, pp. 12–23.
37. Kim, C. G., Park, H. G., Hong, G. H., Kang, S. M. & Lee, H. (2017). Shear strength of concrete composite beams with shear reinforcements. *ACI Structural Journal*, vol. 114(4), pp. 827–838.
38. Kodur, V. K. R. & Shakya, A. M. (2017). Factors governing the shear response of prestressed concrete hollowcore slabs under fire conditions. *Fire Safety Journal*. Elsevier, vol. 88(January), pp. 67–88.
39. Lam, S. S. E., Wong, V. & Lee, R. S. M. (2019). Bonding assessment of semi-precast slabs subjected to flexural load and differential shrinkage. *Engineering Structures*. Elsevier, vol. 187(February), pp. 25–33.
40. Liu, F., Battini, J. M., Pacoste, C. & Granberg, A. (2017). Experimental and Numerical Dynamic Analyses of Hollow Core Concrete Floors. *Structures*. Elsevier, vol. 12(September), pp. 286–297.
41. Liu, J., Ding, F. X., Liu, X. M., Yu, Z. W., Tan, Z. & Huang, J. W. (2019). Flexural Capacity of Steel-Concrete Composite Beams under Hogging Moment. *Advances in Civil Engineering*. Hindawi, vol. 2019.
42. Maazoun, A., Matthys, S., Belkassem, B., Lecompte, D. & Vantomme, J. (2019). Blast response of retrofitted reinforced concrete hollow core slabs under a close distance explosion. *Engineering Structures*. Elsevier, vol. 191(April), pp. 447–459.
43. Meleka, N., Nabil, A. & Heiza, K. M. (2018). PPHC slabs strenthened with different types of concrete toppings. *FIFTEENTH INTERNATIONAL CONFERENCE ON STRUCTURAL AND GEOTECHNICAL ENGINEERING*.
44. Mones, R. M. (2012). Interfacial Strength Between Prestressed Hollow Core Slabs and Cast-In-Place Concrete Topping, (February).
45. Mones, R. M. & Breña, S. F. (2013). Hollow-core slabs with cast-in-place concrete toppings: A study of interfacial shear strength. *PCI Journal*, vol. 58(3), pp. 124–141.
46. Nguyen, T. N. H., Tan, K. H. & Kanda, T. (2019). Investigations on web-shear behavior of deep precast, prestressed concrete hollow core slabs. *Engineering Structures*. Elsevier, vol. 183(August 2018), pp. 579–593.
47. Niwa, J., Fakhruddin, Matsumoto, K., Sato, Y., Yamada, M. & Yamauchi, T. (2016). Experimental study on shear behavior of the interface between old and new deck slabs. *Engineering Structures*. Elsevier Ltd, vol. 126, pp. 278–291.
48. Olalusi, O. B. & Kolawole, J. T. (2018). Probabilistic Safety Analysis of Prestressed Concrete Beams Failing Due to Web-crushing. *Structures*. Elsevier, vol. 15(August), pp. 370–377.
49. Pachalla, S. K. S. & Prakash, S. S. (2017). Load resistance and failure modes of GFRP composite strengthened hollow core slabs with openings. *Materials and Structures/Materiaux et Constructions*. Springer Netherlands, vol. 50(1), pp. 1–14.
50. Park, M. K., Lee, D. H., Han, S. J. & Kim, K. S. (2019). Web-Shear Capacity of Thick Precast Prestressed Hollow-Core Slab Units Produced by Extrusion Method.

International Journal of Concrete Structures and Materials. Springer Singapore, vol. 13(1).
51. Qureshi, L. A. (2018). Effect of Adding Glass Fibre Reinforced Concrete Topping on Flexural Behaviour of Hollow Core Slab Units. *Engineering And Technology Journal*, vol. 03(07).
52. Rahman, M. K., Baluch, M. H., Said, M. K. & Shazali, M. A. (2012). Flexural and Shear Strength of Prestressed Precast Hollow-Core Slabs. *Arabian Journal for Science and Engineering*, vol. 37(2), pp. 443–455.
53. Santos, P. M. D. & Júlio, E. N. B. S. (2013). A state-of-the-art review on roughness quantification methods for concrete surfaces. *Construction and Building Materials*. Elsevier Ltd, vol. 38, pp. 912–923.
54. Schacht, G., Marx, S. & Bolle, G. (2017). Shear load testing of damaged hollow-core slabs. *Structural Concrete*, vol. 18(4), pp. 607–617.
55. Shakya, A. M. & Kodur, V. K. R. (2015). Response of precast prestressed concrete hollowcore slabs under fire conditions. *Engineering Structures*. Elsevier Ltd, vol. 87, pp. 126–138.
56. Shakya, A. M. & Kodur, V. K. R. (2017). Modeling Shear Failure in Precast Prestressed Concrete Hollowcore Slabs under Fire Conditions. *Journal of Structural Engineering (United States)*, vol. 143(9), pp. 1–14.
57. Si, X. T. & Au, F. T. K. (2011). An efficient method for time-dependent analysis of composite beams. *Procedia Engineering*, vol. 14, pp. 1863–1870.
58. Tawadrous, R. & Morcous, G. (2018). Shear strength of deep Hollow-core slabs. *ACI Structural Journal*, vol. 115(3), pp. 699–709.
59. Vadzim Parkhats. (2018). Problem of Cracks in Prestressed Hollow Core Slabs. *Ujęcie aktualnych problemów budownictwa*, (May), pp. 171–180.
60. Wariyatno, N. G., Haryanto, Y. & Sudibyo, G. H. (2017). Flexural Behavior of Precast Hollow Core Slab Using PVC Pipe and Styrofoam with different Reinforcement. *Procedia Engineering*, vol. 171, pp. 909–916.
61. Xiong, C., Chu, M., Liu, J. & Sun, Z. (2018). Shear behavior of precast concrete wall structure based on two-way hollow-core precast panels. *Engineering Structures*. Elsevier, vol. 176(December 2017), pp. 74–89.
62. Xu, X., Yu, J., Wang, S. & Wang, J. (2014). Research and application of active hollow core slabs in building systems for utilizing low energy sources. *Applied Energy*. Elsevier Ltd, vol. 116, pp. 424–435.
63. Yang, Y., Xue, Y., Yu, Y., Ma, N. & Shao, Y. (2017). Experimental study on flexural performance of partially precast steel reinforced concrete beams. *Journal of Constructional Steel Research*. Elsevier Ltd, vol. 133, pp. 192–201.
64. Yu, Y., Wei, B., Yang, Y., Xue, Y. & Xue, H. (2019). Experimental study on flexural performance of steel-reinforced concrete slim floor beams. *Advances in Structural Engineering*, vol. 22(11), pp. 2406–2417.