Behavior of Hybrid Deep Beams Containing Ultra High Performance and Conventional Concretes

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ABSTRACT

This paper presents an experimental investigation consisting of casting and testing twelve rectangular simply supported reinforced concrete deep beams. Three of the tested beams are made with conventional concrete (CC), three with ultra-high performance concrete (UHPC) and six as hybrid beams of the two concrete (UHPC &CC). UHPC is used in compression in the hybrid beams. The effect of these parameters on the behavior of the test beams included deflection, failure mode, and ultimate loads were investigated. Experimental results have generally shown that stiffer load-deflection behavior is obtained with the increase of UHPC layer thickness (h_R/h) and steel fibers volumetric ratio (V_f) for hybrid beams with UHPC in compression.

Key Words: Ultra High Performance Concrete, load-deflection behavior, hybrid deep beams

سلوك العتبات العميقة الهجينة المتكونة من الخرسانة فائقة الاداء و الخرسانة التقليدية

الخلاصة

يقدم هذا البحث تحريا مختبريا يتضمن الصب و الفحص لأثنى عشر عتبة خرسانية مسلحة مستطيلة عميقة المقطع و بسيطة الاسناد. ثلاث عتبات كانت مصنوعة من الخرسانة التقليدية و ثلاث من الخرسانة فائقة الاداءة وست كعتبات هجينة من الخرسانتين(فائقة الاداء و التقليدية). استخدمت الخرسانة فائقة الاداءة في منطقة الانضغاط في العتبات الهجينة. وتم ايضا دراسة تاثير هذه المتغيرات مع تصرف عتبات الاختبار الذي شمل الهطول ،نوع الفشل والحمل الاقصى لها. اظهرت النتائج المختبرية عموماً انه تم الحصول على سلوك الحمل-الهطول اكثر صلادة عند زيادة سمك طبقة الخرسانةفائقة الاداء و نسبة الياف الحديد للعتبات الهجينة ذات الخرسانةفائقة الاداءا في منطقة الانضغاط.

الكلمات المرشدة: الخرسانة فائقة الاداءة،مقاومة الانثناء،العتبات الهجينة العميقة.

INTRODUCTION

Reinforced concrete deep beams are structural members having depth much greater than normal in relation to their span, while the thickness in the perpendicular direction is much smaller than either span or depth[1]. These members are used in many structural applications such as diaphragms, water tanks,

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foundations, bunkers, shear walls, girders used in multi-story buildings to provide column offsets, and floor slabs under horizontal loads[1,2].

Reactive powder concrete (RPC), which is now more generally described as ultra-high performance concrete (UHPC) [3], has attracted the attention of researchers and practitioners since its introduction in the 1990s, not only because of its high compressive strength but also because of its excellent environmental resistance (durability).

The addition of fibers to UHPC further improves tensile cracking resistance, post cracking strength, ductility and energy absorption capacity [4].

RPC is cement based composite material formulated by combining cement, silica fume, fine sand, high range water reducer, water and steel or organic fibers. It is a special concrete in which the microstructure is optimized by precise gradation of all particles to yield maximum density [5, 6, 7].

RPC mixes are characterized by high silica fume content and very low water-cement ratio. Coarse aggregate is eliminated to avoid weaknesses of the microstructure and heat treatment is applied to achieve high strength [8,9]. RPC is composed of particles of similar moduli and size which helps in increasing the homogeneity thereby reducing the differential tensile strain in the concrete and consequently increasing the ultimate load carrying capacity of RPC [6].

Owing to the fineness of silica fume and the increased quantity of hydraulically active components, it has been called reactive powder concrete [10].

Since its first introduction at the 1990s, many RPC applications of prototype structures have been constructed in various countries such as France, USA, Germany, Canada, Japan, South Korea, Australia, New Zealand and Malaysia[11].

RPC was first developed by Richard and Cheyrezy (1995)[8] in the early 1990s. They reported achieving compressive strength in the range 200-800 MPa and fracture energies up to 40 kj/m^2. Their work depends on the following basic principles:

- Enhancement of homogeneity by elimination of coarse aggregate.
- Enhancement of compacted density by optimization of the granular mixture, and application of pressure before and during setting.
- Enhancement of the microstructure by post-set heat treatment.
- Enhancement of ductility by incorporating steel fibers.

Wille et al. (2011) [3] developed an UHPC of more than 150 MPa compressive strength without the need for either heat curing or pressure using a conventional concrete mixer. The developed UHPC mixtures had the additional benefit of exhibiting high workability. They recommended the following mixing procedure to obtain the mentioned advantages:

1. Mix silica fume and sand first for 5 minutes.
2. Add other dry components (cement and glass powder) and mix for another 5 minutes.
3. Add all the water within 1 minute.
4. Add all the superplasticizer and mix for an additional 5 minutes.
5. Add coarse aggregate, if applicable, and mix for an additional 3 minutes.
6. Add fibers, if applicable, and mix for an additional 2 minutes.

It should be mentioned, here, that nearly all local researches on RPC used heat curing (with or without presetting pressure) to develop the desired mechanical properties. Based on the information obtained from previous works, the present study is the first local study (with other simultaneously and independently performed studies at the University of Mustansiriya / College of Engineering) to produce RPC of compressive strength more than 120 MPa using normal water curing at ambient temperature without presetting pressure. This makes the production of RPC more economic and more practical choice especially in field applications.

USE OF UHPC IN HYBRID ELEMENTS

Design criteria of hybrid elements is based on the concept that the use of the materials of improved performance (such as HSC, HPC and UHPC), which are relatively expensive materials, should be limited to parts in the structure subjected to severe environmental conditions and/or when stiffness or resistance of the structural element must be increased without increasing the dead weight or at points of concentrated load application, while other parts of the structure consist of conventional concrete[12].

Denarie et al. (2003)[13] tested a composite UHPFRC and conventional reinforced concrete (RC) beams to ultimate flexural strength. These composite beams comprised of an UHPFRC overlay to replace the standard tensile reinforcing bars in a RC beam and exhibited an ultimate force comparable to the standard RC beams.

Alaee and Karihaloo (2003) [14] used UHPFRC as bonded strips applied to the tensile face to rehabilitate and improve existing reinforced concrete beams.

The rehabilitated composite beams behaved monolithically until fracture with ultimate force equal to or higher than the reference concrete member, but experienced a softening phase after reaching the ultimate force.

Habel et al. (2007) [15] investigated the flexural behavior of composite beams. The beams composed of RC substrates and UHPFRC layers in the tension face as shown in Figure (1). They concluded that applying UHPFRC layer to form a composite beam increases stiffness, minimizes deformations for given imposed loads, reduces crack widths and crack spacing and delays the formation of localized macrocracks as compared to the original conventionally reinforced concrete beams.

They found also that the composite beams behaved monolithically and debonding only occurred near the ultimate load for beams without reinforcing bars in UHPFRC layer whereas the presence of such bars in UHPFRC prevents debonding.

Raj and Jeenu (2010)[5] investigated the flexural behavior of composite beams whose top (compression) layers were made of UHPC of compressive strength greater than 80 MPa and the lower (tension) layers are of 25 MPa compressive strength normal concrete.

They concluded that the ultimate load of composite beams with 5 cm and 10 cm UHPC layer (beam overall depth is 20 cm) increases by 38% and 62% respectively compared to normal strength concrete beams. Energy absorption was also increased using composite beams.

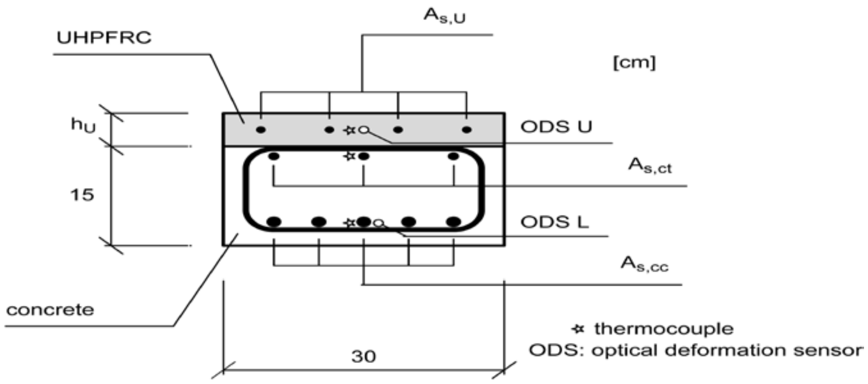


Figure (1) Cross-section of the composite "UHPFRC-concrete" beams [15]

EXPERIMENTAL WORK

The experimental work of this study consists of casting and testing twelve rectangular simply supported reinforced concrete deep beams. Three of these beams are made with conventional concrete (CC), three with ultra-high performance concrete (UHPC and six as hybrid beams of the two concretes (UHPC & CC). UHPC is used in compression. Details of all experimental work stages are presented in the following.

Materials

Cement

Ordinary Portland cement (type I) manufactured by the united cement company (UCC) in Iraq was used throughout the experimental work of this study for both CC and UHPC.

Fine Aggregate

Natural sand was used for CC mixes while fine sand with maximum particle size of 600µm was used for UHPC mixes.

Coarse Aggregate

Crushed river gravel with maximum particle size of 10mm was used as coarse aggregate for CC mixes only while coarse aggregate with maximum particle size of 5mm was used for UHPC mixes.

Silica Fume

A grey colored densified silica fume was used as an admixture in UHPC mixes to enhance its properties. The fineness of the used silica fume is 200 000 m^2/kg and its chemical composition is given in Table (1).

Table (1) Chemical Analysis of Silica Fume

Chemical Composition	Percent %
SiO_2	98.87
Al_2O_3	0.01
Fe_2O_3	0.01
CaO	0.23
MgO	0.01
K_2O	0.08
Na_2O	0.00

According to manufacturer editions.

Superplasticizer

A superplasticizer commercially named Sika Visco Crete PC-20 was used as an admixture to produce UHPC in this study. Some properties of this superplasticizer are given in Table (2).

Table (2) Properties of Sika Visco Crete PC-20*

Main action	**Concrete superplasticizer**
Appearance/Colures	Light brownish liquid
Chemical base	Modified polycarboxylates based polymer
Density	1.09 kg/l, at 20 °C
PH	7
Chloride ion content%	Free
Effect on setting	Non-retarding
Storage life	12 months from date of productionif stored properly in original, at temperatures between +5°C and +35°C. Protect from direct sunlight and frost.

According to manufacturer editions.

Steel Fibers

Micro straight steel fibers with aspect ratio (L/d) of 52 were used in UHPC mixes. Sample of the used steel fibers is shown in Figure (2) and their properties are listed in Table(3).

Figure (2) Sample of micro steel fibers used in present investigation

Table (3) Properties of steel fibers used*

Type of steel	**Straight**
Relative Density	7800 kg/m3
Yield strength	1130 MPa
Modulus of Elasticity	205 000 MPa
Strain at proportion limit	5650*10-6
Poisson's ratio	0.28
Average length (L)	13.1 mm
Nominal diameter (d)	0.25
Aspect ratio (length/diameter)	52

According to manufacturer editions.

Steel Reinforcement

Deformed steel bars are used in this work with nominal diameters of 16 mm and 10 mm for longitudinal reinforcement in tension side (bottom side) and plain bars of diameter 4 mm are used for longitudinal reinforcement in compression side (top side) while deformed bars of 4 mm is used as vertical shear reinforcement. The result of testing this bars met ASTM A615 [16] requirements for Grade 60 steel. The test results are listed in Table (3). Steel reinforcing cages are shown in Figure (3).

Table (4) Properties of reinforcing steel bars

Nominalbar diameter(mm)	Bar area (mm^2)	Yield stress(MPa)	Ultimate stress(MPa)	Elongation at ultimate stress (%)
16	201	671	831	6.6
10	78.5	650	807	9.7
4	12.6	406	534	3.4
ASTM A615 [16] limits		420	620	9

Figure (3) Steel reinforcement cage used for beams construction

Mix Proportions

Table (5) gives mix proportions of CC and UHPC mixes used in different beams. Based on several trial mixes, three CC mixes and three UHPC mixes that differ from each other only in volumetric steel fibers ratio (V_f) were adopted in this study.

Table (5) Mix proportions of CC and UHPC

Concrete Type	CC			UHPC		
Cement (C) (kg/m^3)	400			900		
Sand (S) (kg/m^3)	600			475		
Gravel (G) (kg/m^3)	1200			475		
Silica Fume (SF) (kg/m^3)	-			225*		
Super-plasticizer (SP) (kg/m^3)	-			56.25**		
Water (W) (kg/m^3)	200			180		
W/C	0.5			0.2***		
Steel Fibers (kg/m^3)	0	39	78	0	39	78
V_f (%)	0	0.5	1	0	0.5	1

SF/C = 25%

SP/(C+SF) = 5%

W/(C+SF) = 0.16

Mixing and Casting

Wooden molds were used for beams with inner dimensions of 100mm in width, 330mm in depth and 1050mm in length. After cleaning, oiling inner surfaces and fastening the parts of the mold, the steel reinforcement was placed in its required position in the mold.

Mixing was done using a horizontal rotary mixer of 0.19m^3 capacity. CC was mixed in a classical procedure where gravel and sand were mixed first for 2 minutes then cement was added and the dry components were mixed for about 3 minutes to obtain a homogeneous dry mix, then water was added during the mixing process which continued for another 3 minutes or until obtaining a homogeneous mixture.

Mixing procedure proposed by Wille et al. (2011) [3] was adopted in this study to produce UHPC in a simple way without any accelerated curing regimes. Fine sand and silica fume were first mixed for 4 minutes, then cement was added and the dry components were mixed for 5 minutes. Superplasticizer was added to the water, then the blended liquid was added to the dry mix during the mixer rotation and the mixing process continued for another 3 minutes. Finally, steel fibers were added during mixing within 2 minutes. The total mixing time of RPC was about 15 minutes.

Casting of CC and UHPC beams was done by placing the specific concrete into molds continuously in three layers with each layer being vibrated using a table vibrator to obtain a more compacted concrete.

For hybrid beams (two layers beams), bottom layer CC was mixed and placed first, then, the top layer (UHPC) was mixed and placed above the first one. The time period between the placing of the two layers was about 30 minutes where the top surface of the bottom layer was left rough to ensure good interaction between the two layers.

With each mix control specimens were cast to determine the mechanical properties of concrete. Control specimens involve 3 cylinders (100mm×200 mm) for compressive strength, 3 cylinders (100mm×200mm) for splitting tensile strength, 3 cylinders (150mm×300mm) for modulus of elasticity and 3 prisms (100mm×100mm×500mm) for flexural strength (modulus of rupture).

After casting, all specimens were covered with a nylon sheet for 24 hours to prevent loss of moisture.

Curing of Specimens

After 24 hours from casting, all specimens were demolded and placed in water containers in the laboratory to be cured at room temperature. This normal curing method was applied for CC as well as UHPC.

In the previous works, UHPC was always produced using accelerated curing methods such as heat curing at elevated temperature or presetting pressure. Any of these methods was not used in this study in order to gain an advantage of producing UHPC of exceptional mechanical properties (compressive strength up to 120 MPa) using conventional curing method without any additional provisions. This was proved to be successful as will be seen in this paper.

However, this normal curing was proposed by Wille et al [3] as part of their proposed simpler way to produce UHPC and the mixing procedure used in this study was the main part of their proposal.

Specimens were taken out of containers after 28 days of water curing and kept in the laboratory until testing.

Details and Designation of Beams

Twelve beams of dimensions (100mm×330mm×1050mm) were cast and tested in this study. Three of these beams are made with CC, three with UHPC and six as hybrid beams of two layers (CC & UHPC). UHPC was used in compression, three volumetric steel ratios (V_f =0%, 0.5% and 1%) were used in the tested beams. Shear reinforcement (stirrups) were kept constant in all beams with sufficient quantity (4mm stirrups at 100mm spacing). Steel plate under load with dimensions 35×35 mm, as shown in Figure (4). The details of the tested deep beams are shown in the Table (6). Figure (5) shows the details and types of the tested beams.

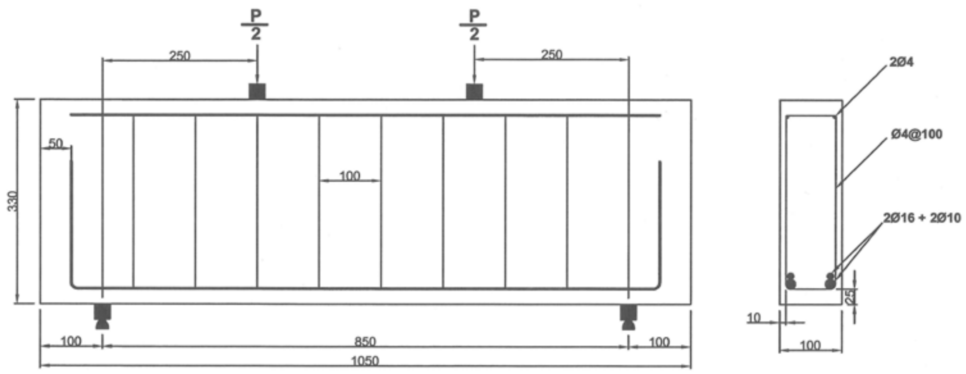


Figure (4) Typical dimensions (mm) and details of tested deep beam

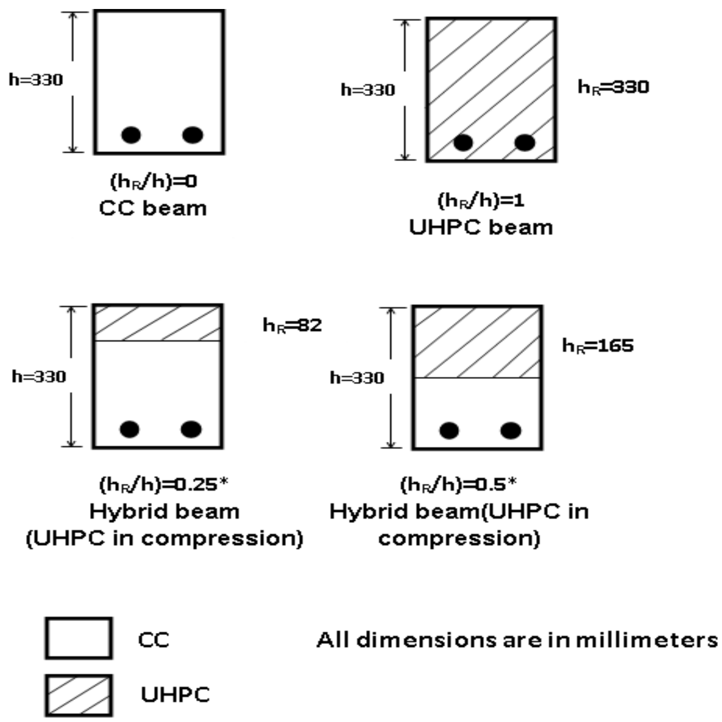


Figure (5) Types of the tested beams

Table (6) Details of tested beams and research parameters

Group	Beam designation	Beam Dimensions mm	Conc. Type	h_R (mm)	h_R/h	a/d	V_f %
A	A0	1050×100 × 330	CC	0	0	1	0
	A1	1050×100 × 330	CC	0	0	1	0.5
	A2	1050×100 × 330	CC	0	0	1	1
B	B0	1050×100 × 330	UHPC	330	1	1	0
	B1	1050×100 × 330	UHPC	330	1	1	0.5
	B2	1050×100 × 330	UHPC	330	1	1	1
C	C0	1050×100 × 330	UHPC + CC	82.5	0.25	1	0
	C1	1050×100 × 330	UHPC + CC	82.5	0.25	1	0.5
	C2	1050×100 × 330	UHPC + CC	82.5	0.25	1	1
D	D0	1050×100 × 330	UHPC + CC	165	0.5	1	0
	D1	1050×100 × 330	UHPC + CC	165	0.5	1	0.5
	D2	1050×100 × 330	UHPC + CC	165	0.5	1	1

Tests and Measurements of Deep Beams

All beams were tested using a hydraulically universal testing machine of 3000 kN capacity under monotonic loads up to ultimate load at the Structural Laboratory of the College of Engineering of Al-Mustansiriya University. Vertical deflections are measured at deep beam midspan using digital gauge of (0.01 mm) accuracy. Loading was applied at increments of 10 kN. At each load stage the deflection readings at the midspan of beam were recorded. When the first crack appeared, the load corresponding to it was recorded.

Figure (6) Digital gauge position

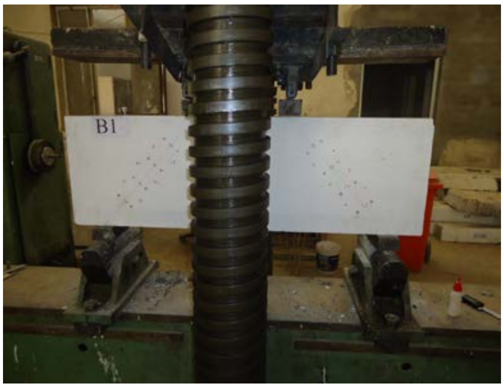


Figure (7) Deep beam inside machine

MECHANICAL PROPERTIES RESULTS FOR CC AND UHPC

Tests results of mechanical properties (compressive strength, modulus of elasticity, flexural strength and splitting tensile strength) of CC and UHPC are shown in Table (7) and Figures (8) to (11).

Results show that when steel fibers ratio increases from 0% to 1%, in UHPC, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength increase by 28.98%, 32.56%, 85.76% and 84.53%, respectively.

It is clearly shown that the effect of steel fibers on flexural strength and splitting tensile strength is higher than that on compressive strength and modulus of elasticity. This assures that steel fibers are used mainly to improve tensile properties of UHPC.

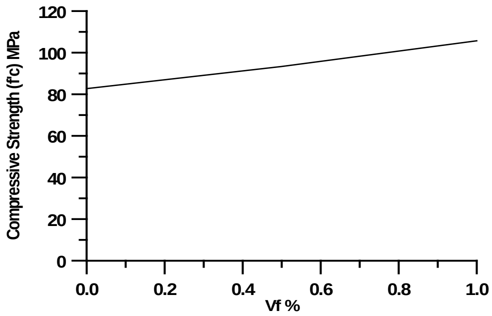


Figure (8) Effect of steel fibers ratio on compressive strength of UHPC.

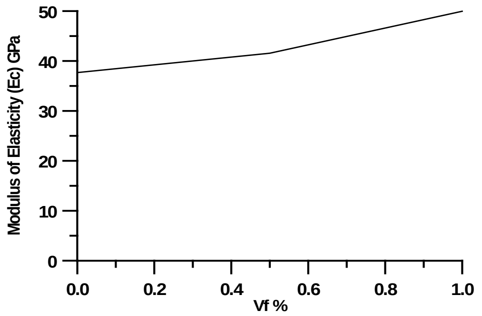


Figure (9) Effect of steel fibers ratio on modulus of elasticity of UHPC.

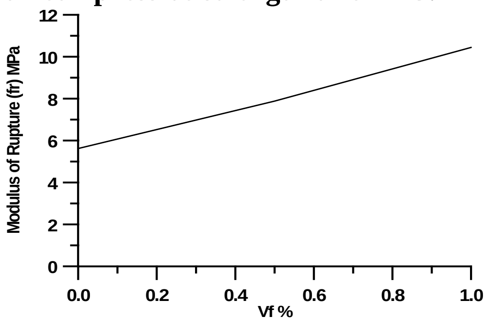


Figure (10) Effect of steel fibers ratio on modulus of rupture of UHPC.

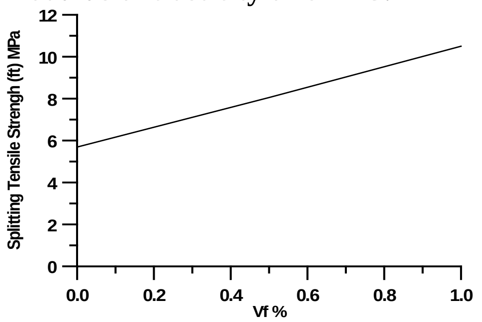


Figure (11) Effect of steel fibers ratio on splitting tensile strength of UHPC.

TEST RESULTS OF DEEP BEAMS

Ultimate Failure Load

Table (8) summarizes the results of first cracking load (P_{cr}) and ultimate load (P_u) for all tested beams together with their modes of failure.

Table (7) Mechanical properties of CC and UHPC.

Type of Concrete	Steel Fibers Ratio (V_f) (%)		Cylinder Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Flexural Strength (MPa)	Splitting Tensile Strength(MPa)
CC	0	Test result	32.84	24.89	4.41	3.12
		Increasing ratio (%)	0	0	0	0
	0.5	Test result	33.29	25.36	6.32	3.78
		Increasing ratio (%)	1.37	1.88	43.31	21.15
	1	Test result	34.54	26.18	7.02	4.15
		Increasing ratio (%)	5.17	5.17	59.18	33.01
UHPC	0	Test result	82.72	37.68	5.62	5.69
		Increasing ratio (%)	0	0	0	0
	0.5	Test result	93.33	41.55	7.88	8.05
		Increasing ratio (%)	12.82	10.27	40.21	41.47
	1	Test result	105.7	49.95	10.44	10.5
		Increasing ratio (%)	27.78	32.56	85.76	84.53

Table (8) Tests results of tested deep beams

Beam name	Concrete Type	h_R/h	V_f %	P_{cr} kN	P_u kN	Mode of shear failure
A0	CC	0	0	125	370	Diagonal tension failure
A1	CC	0	0.5	170	395	Diagonal tension failure
A2	CC	0	1	210	465	Diagonal tension failure
B0	UHPC	1	0	215	1040	Diagonal tension failure
B1	UHPC	1	0.5	250	1500	(Shear +flexural) failure
B2	UHPC	1	1	320	1695	(Shear +flexural) failure
C0	UHPC+CC	0.25	0	140	520	Diagonal tension failure
C1	UHPC+CC	0.25	0.5	190	630	Diagonal tension failure
C2	UHPC+CC	0.25	1	225	690	Diagonal tension failure
D0	UHPC+CC	0.5	0	160	840	Diagonal tension failure
D1	UHPC+CC	0.5	0.5	200	985	Diagonal tension failure
D2	UHPC+CC	0.5	1	230	1020	Diagonal tension failure

Effect of Volumetric Steel Fiber Ratio (V_f)

Effect of (V_f) on cracking and ultimate loads and the ratio of them for all tested beams are detailed in Tables (9) and (10). The improvement in ultimate load value due to increasing (V_f) from 0 % to 0.5 % ranges from 6.75 % to 44.23 % (25.49 % as a typical average improvement for two cases). The improvement in UHPC beams is larger than the improvement in CC beams. The improvement in ultimate load due to increasing (V_f) from 0 % to 1 % ranges from 25.67 % to 62.98 % (44.32 % as a typical average improvement for two cases).

The improvement in cracking load due to increasing (V_f) from 0.0 % to 0.5 % ranges from 16.27 % to 36 % (26.13% as a typical average improvement for two cases). The improvement in cracking load due to increasing (V_f) from 0 % to 1 % ranges from 48.83 % to 68 % (58.41 % as typical average improvement for two cases). Generally, the improvements in UHPC beams are higher than the improvements in CC beams.

The presence of steel fibers results in a delay in crack initiation and propagation where they hold concrete particles and prevent them from initial separation. Therefore, the first crack in fibrous concrete beams appears at a load level appreciably higher than the load which causes crack initiation in non-fibrous concrete beam. After cracking, the steel fibers prevent the crack widening and delay its growth by absorption a portion of tension stresses carried by concrete i.e., this action reduces the tension stresses applied to concrete. Therefore, the failure takes place in fibrous concrete beams at a load level higher than that load causing the failure of non-fibrous concrete beams. The ratio between cracking and ultimate loads increases with increasing steel fiber ratio, where it ranges from 0.21 to 0.338 for non-fibrous concrete beams and ranges from 0.17 to 0.43 for fibrous concrete beams with 0.5 %

of steel fibers. While the ratio ranges from 0.19 to 0.452 for fibrous concrete beams with 1 % of steel fibers.

Table (9) Effect of using 0.5 % of steel fibers on cracking and ultimate loads

	Strength type	V_f= 0.0 %			V_f= 0.5 %			% Variation due to increasing (% V_f)	
		P_{cr} kN	P_u kN	P_{cr}/P_u	P_{cr} kN	P_u kN	P_{cr}/P_u	P_{cr} %	P_u %
a / d = 1	CC	125	370	33.8	170	395	43	36	6.75
	UHPC	215	1040	0.21	250	1500	17	16.27	44.23

Table (10) Effect of using 1 % of steel fibers on cracking and ultimate loads

	Strength type	V_f= 0.0 %			V_f= 1%			% Variation due to increasing (% V_f)	
		P_{cr} kN	P_u kN	P_{cr}/P_u	P_{cr} kN	P_u kN	P_{cr}/P_u	P_{cr} %	P_u %
a / d = 1	CC	125	370	33.8	210	465	45.2	68	25.67
	UHPC	215	1040	0.21	320	1695	0.19	48.83	62.98

Effect of UHPC Layer Thickness (h_R/h)

Hybrid beams exhibit a stiffer behavior than the CC beam especially when using steel fibers ratio of 1%. Only a slight increase in stiffness was observed when (h_R/h) increases from 0.25 to 0.5 while UHPC beams show slightly lower stiffness than hybrid beams. This lower stiffness of UHPC beams may be attributed to the low content of coarse aggregate and to the presence of shrinkage cracking caused by rapid drying which may occur because of the very low water to cement ratio in UHPC.

Effect of (h/h_R) on cracking and ultimate loads and the ratio of them for all tested beams are detailed in Tables (11) to (13). The improvement in ultimate load value due to increasing (h/h_R) from 0 to 0.25 ranges from 40.54 % to 59.49 % (49.47 % as a typical average improvement for all three cases). The improvement in ultimate load due to increasing (h/h_R) from 0 to 0.5 ranges from 119.35 % to 149.36 % (131.9 % as a typical average improvement for all three cases),and the improvement in ultimate load due to increasing (h/h_R) from 0 to 1 ranges from 181.1 % to 279.75 % (241.78 % as a typical average improvement for all three cases).

The improvement in cracking load due to increasing (h/h_R) from 0 to 0.25 ranges from 7.14 % to 11.76 % (9.87% as a typical average improvement for all three cases). The improvement in cracking load due to increasing (h/h_R) from 0 to 0.5 ranges from 9.52 % to 28 % (18.38 % as typical average improvement for all three cases), and the improvement in ultimate load due to increasing (h/h_R) from 0 to 1 ranges from 47.06 % to 72% (57.15 % as a typical average improvement for all three cases).

Table (11) Effect of increasing (h/h_R) from 0 to 0.25 on cracking and ultimate loads

Beam name	Concrete Type	h_R/h	V_f %	P_{cr} kN	P_{cr} %	P_u kN	P_u %
A0	CC	0	0	125	10.71	370	40.54
C0	UHPC+CC	0.25	0	140		520	
A1	CC	0	0.5	170	11.76	395	59.49
C1	UHPC+CC	0.25	0.5	190		630	
A2	CC	0	1	210	7.14	465	48.38
C2	UHPC+CC	0.25	1	225		690	

Table (12) Effect of increasing (h/h_R) from 0 to 0. 5 on cracking and ultimate loads

Beam name	Concrete Type	h_R/h	V_f %	P_{cr} kN	P_{cr} %	P_u kN	P_u %
A0	CC	0	0	125	28	370	127
D0	UHPC+CC	0.5	0	160		840	
A1	CC	0	0.5	170	17.64	395	149.36
D1	UHPC+CC	0.5	0.5	200		985	
A2	CC	0	1	210	9.52	465	119.35
D2	UHPC+CC	0.5	1	230		1020	

Table (13) Effect of increasing (h/h_R) from 0 to 1 on cracking and ultimate loads

Beam name	Concrete Type	h_R/h	V_f %	P_{cr} kN	P_{cr} %	P_u kN	P_u %
A0	CC	0	0	125	72	370	181.1
B0	UHPC	1	0	215		1040	
A1	CC	0	0.5	170	47.06	395	279.75
B1	UHPC	1	0.5	250		1500	
A2	CC	0	1	210	52.38	465	264.51
B2	UHPC	1	1	320		1695	

Load-Mid Deflection Relationships

From the load-midspan deflection relationship shown in Figures 12 to 15 for all deep beams, the following three distinct stages are observed:

1. The first stage shows linear behavior with constant slope.
2. In the second stage, vertical flexural cracks were initiated at the tensile face within the maximum bending moment region of the beam, and extend upward, then inclined cracks originated in the shear spans. These cracks developed with increased load, causing a corresponding shift of the neutral axis towards the compression face, and consequently, a continuous reduction in the moment of inertia of the cracked section. The curve changed from linear to non-linear behavior in this stage.
3. In the third stage, the shape of the load-deflection curve tends to be asymptotic to the horizontal as the beam approached its ultimate load.

Effect of Steel Fibers Ratio (V_f)

Generally, when steel fibers ratio increases from 0% to 1%, the stiffness of hybrid beams with UHPC and UHPC beams increases too with very clear effect of 1% steel fibers as shown in Figures (12 to 15).

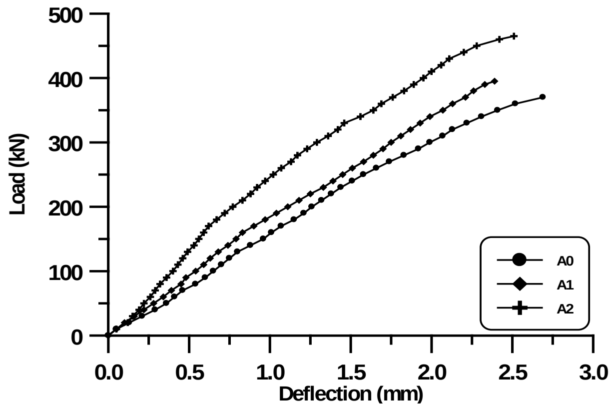


Figure (12) Load-Deflection Relationship of CC Deep Beams

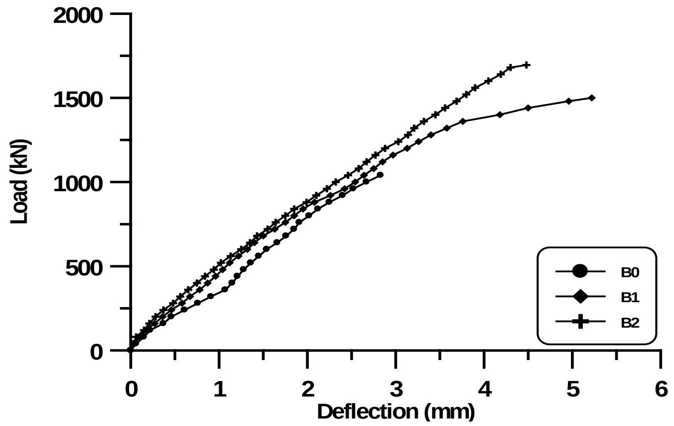


Figure (13) Load-Deflection Relationship of UHPC(hR/h=1) Deep Beams

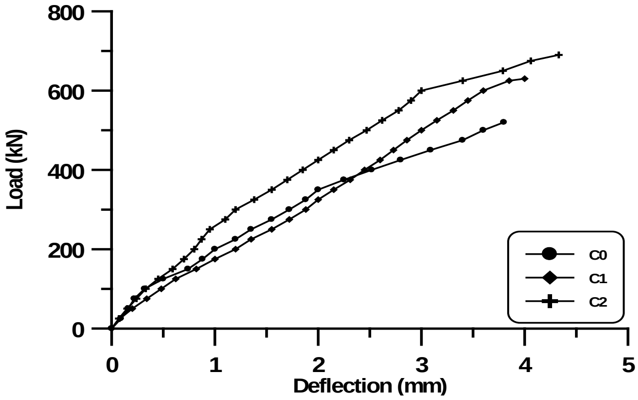


Figure (14) Load-Deflection Relationship of Hybrid Deep Beams (hR/h=0.25)

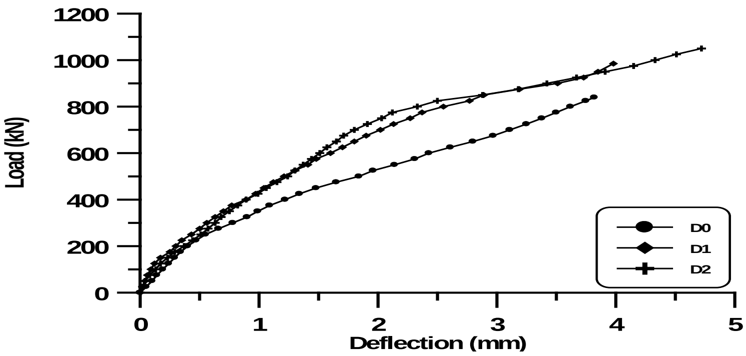
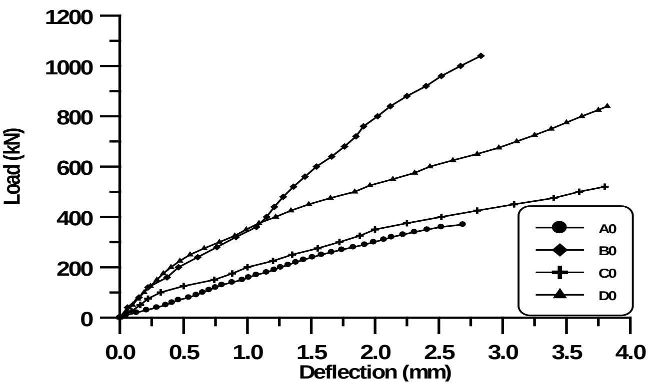


Figure (15) Load-Deflection Relationship of Hybrid Deep Beams (hR/h=0. 5)

Effect of UHPC Layer Thickness (h_R/h)

Hybrid beams exhibit a stiffer behavior than the CC beams especially when using steel fibers ratio of 1%. Only a slight increase in stiffness was observed when (h_R/h) increases from 0.25 to 0.5 while UHPC beams show slightly higher stiffness than hybrid beams as may be shown in Figures (16 to 18). This lower stiffness of UHPC beams may be attributed to the low content of coarse aggregate and to the presence of shrinkage cracking caused by rapid drying which may occur because of the very low water to cement ratio in UHPC.



with (Vf=0%) Figure (16)Effect of UHPC layer thickness on load-deflection of Deep beams

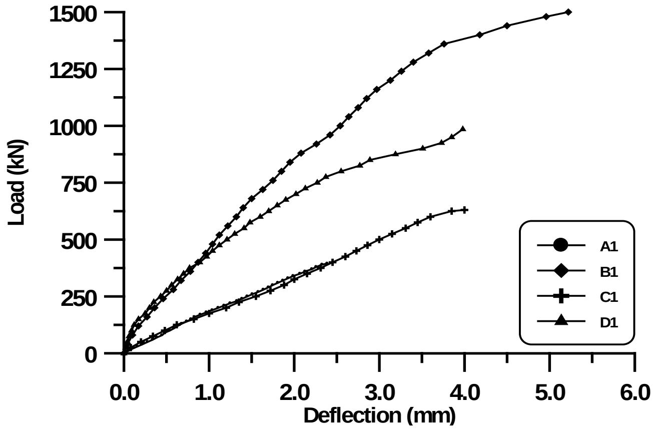


Figure (17) Effect of UHPC layer thickness on load-deflection of Deep beams with (Vf=0.5%)

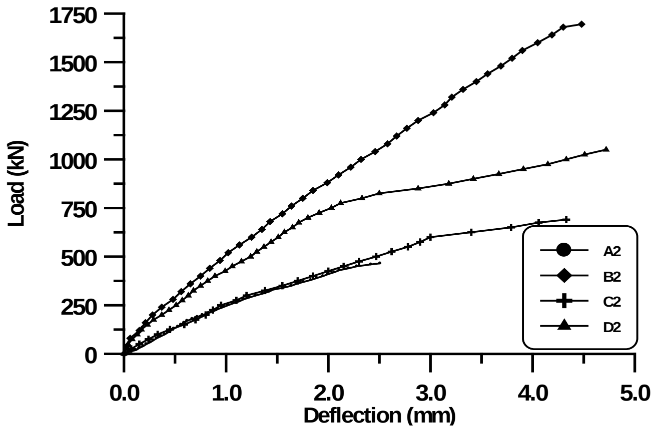


Figure (18) Effect of UHPC layer thickness on load-deflection of Deep beams with (Vf=1%)

Failure Mode:

Figure 19 shows the crack patterns after testing all the beams to failure. This plate shows that the failure mode for most of the deep beams tested was through a diagonal shear crack with different widths extending from the bottom of beam near the support to the loading points at the top with different widths. The cracks were accompanied, in some specimens, by the formation of new inclined cracks parallel to the initial cracks in the shear span. However, three specimens failed by flexural vertical cracks extended to the compression zone. The diagonal cracks extended towards the beam's bottom at or near the supports and the loading points at the top but did not reach both.

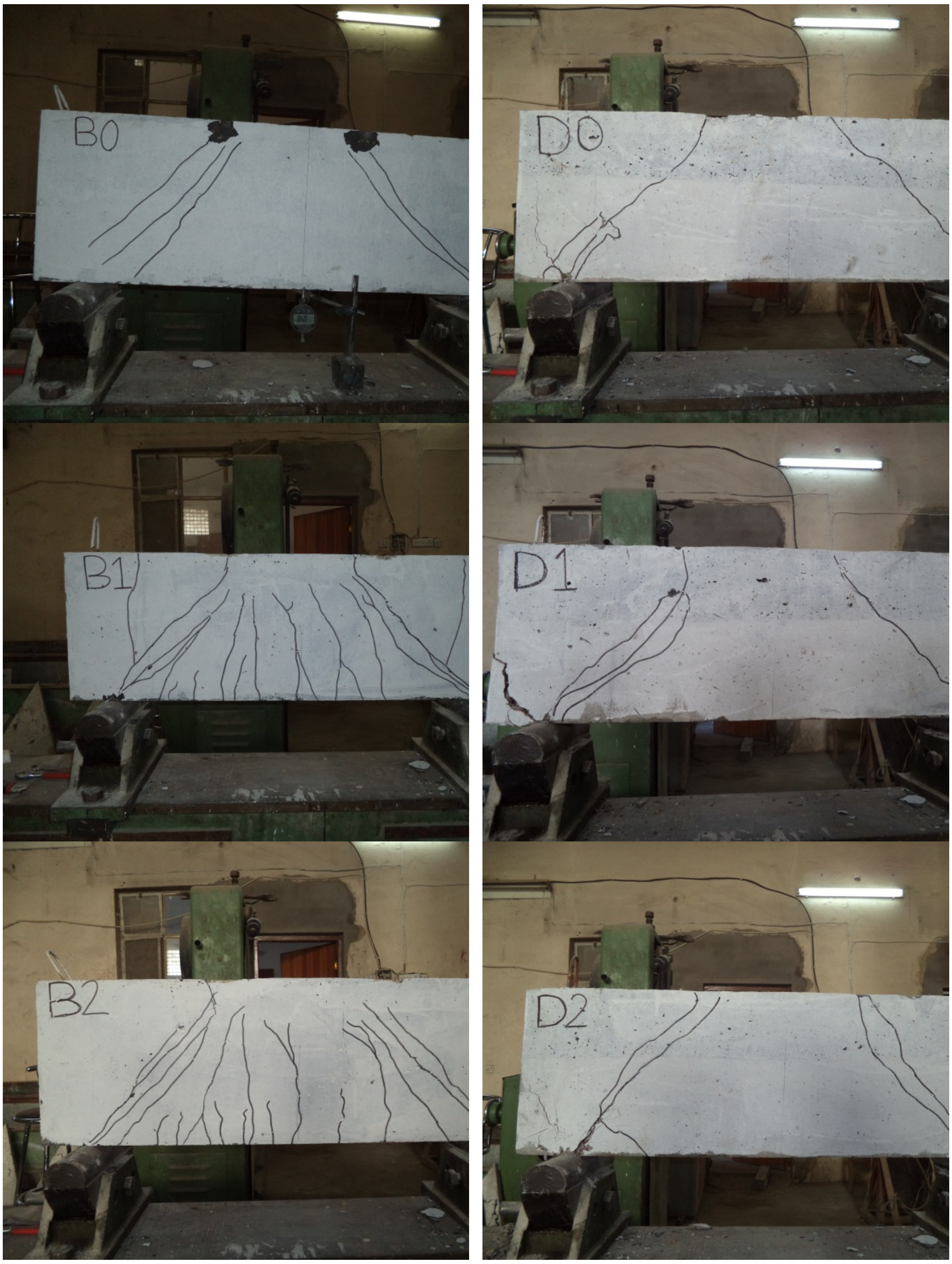


Figure (19) Beam specimens after testing to failure

STRUT AND TIE MODEL FOR RPC DEEP BEAMS

In deep beams without web reinforcement, the shear force is resisted primarily by the strut forming between the loading point and the support. For beams in which flexural, bearing and anchorage failures are prevented, the shear capacity is governed by the compressive capacity of the strut, which is a function of the strut dimensions. The strut is usually assumed to be a bottle shaped strut. A simple idealization of the shape of strut is adopted as shown in Figure 20.

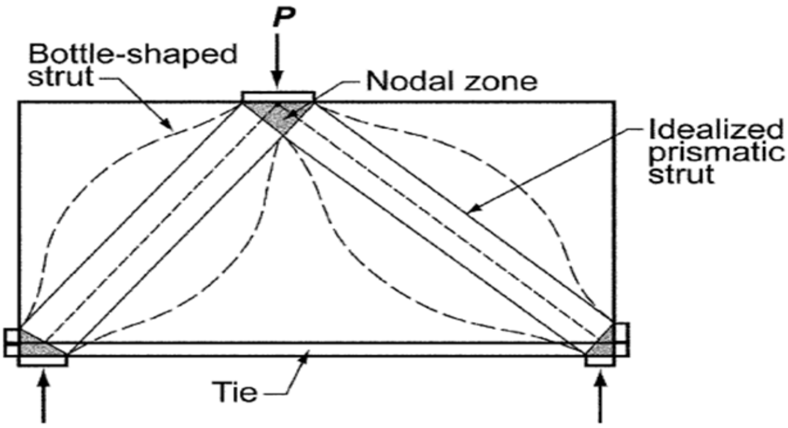


Figure 20: Shape of strut[17]

According to ACI 318-11[17] Code, the nominal compressive strength of a strut should be taken as:

$$F_{ns} = f_{ce} A_{cs} \qquad \dots (1)$$

where,
A_{cs} = area of strut.
f_{ce} = compressive stress in the strut given by:

$$f_{ce} = 0.85 \beta_s f_c' \qquad \dots (2)$$

where,
β_s = 0.60 for strut without web reinforcement.
β_s = 0.75 for strut with web reinforcement satisfying (Figure 21):

$$\rho_p = \sum \frac{A_{si}}{b_s s_i} \sin \alpha_i \geq 0.003 \qquad \dots (3)$$

where,
A_{si} = total area of surface reinforcement at spacing s_i in the *i*-th layer crossing a strut, with reinforcement at an angle α_i to the axis of the strut.
b_s = width of strut
α_i = angle between *i*-th layer of reinforcement and axis of strut
s_i = spacing of reinforcement in *i*-th layer

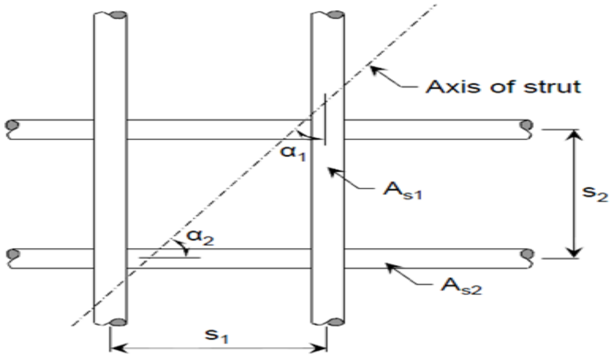


Figure 21: Calculation of web reinforcement in ACI 318-11[17]

The strut and tie model is applied to the tested hybrid beams , the results shown in Table (14) indicates that the ACI strut strength computed results is lower values than the experimental, the predicted values are enhanced when using ACI equations with web reinforced strut.

Table 14: Experimental and predicted failure loads using ACI recommendations

Beam No.	Experimental failure load kN(1)	Predicted		Ratios	
		ACI without web reinf. = 0.6 (2)β_s	ACI with web reinf. = 0.75 (3)β_s	(2)/(1)	(3)/(1)
A0	370	273	341.5	0.738	0.923
A1	395	297.45	371.7	0.753	0.941
A2	465	346.9	433.85	0.746	0.933
B0	1040	756.1	945.36	0.727	0.909
B1	1500	1081.5	1351.5	0.721	0.901
B2	1695	1095	1369.56	0.646	0.808
C0	520	360.88	451.36	0.694	0.868
C1	630	448	560.1	0.711	0.889
C2	690	500.25	625.14	0.725	0.906
D0	840	600.6	751	0.715	0.894
D1	985	720	900.3	0.731	0.914
D2	1020	757	946.56	0.742	0.928
			Average	**0.720**	**0.901**

CONCLUSIONS

Based on the results obtained in the present work from the experimental tests for the conventional, hybrid and ultra-high performance concrete deep beams, the following conclusions can be drawn:

1. It is possible to produce UHPC with compressive strength of 105.7MPa, modulus of elasticity of 49.95 GPa, flexural strength of 10.44MPa and splitting tensile strength of 10.5 MPa using normal water curing at room temperature and without the application of pressure and heat curing.
2. When steel fibers ratio increases from 0% to 1%, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength increase by

27.78%, 32.56 %, 85.76% and 84.53%, respectively. The effect of steel fibers on flexural strength and splitting tensile strength is clearly higher than that on compressive strength and modulus of elasticity. This assures that steel fibers are used mainly to improve tensile properties of UHPC.

3. All tested deep beams were failed by shear. The shear failure took place by diagonal tension mode for all tested beams except beam (B1 &B2) where the addition of steel fibers change the mode of failure to (shear + flexure).

4. It was found that the use of 0.5 % of steel fibers increases the cracking load by a range of 16.27 % to 36 % (the average of increase is 26.13 %). While, the use of 1 % of steel fibers increases the cracking load with a range of 48.83 % to 68 % (the average of increase is 58.42 %). The improvements are generally larger in UHPC beams when compared with CC beams.

5. The presence of 0.5 % of steel fibers increases the ultimate load by a range of 6.75 % to 44.23 % (the average of increase is 25.49 %). While using of 1 % of steel fibers increases the ultimate load with a range of 25.67% to 62.98 % (the average of increase is 44.33 %). The enhancement is larger in UHPC beams when compared with CC beams.

6. When steel fibers ratio increases from 0% to 1%, the stiffness of hybrid and UHPC beams increases too with very clear effect of 1% steel fibers.

7. The predicted hybrid deep beam strength using the ACI strut and tie model are underestimated with comparison in the experimental values by up to about 28%.

8. Using a reduction factor of β_s = 0.75 results in improved prediction values of the shear strength of hybrid deep beams by 10% difference between experimental and computed values.

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NOTATIONS

CC	Conventional concrete
UHPC	Ultra high performance concrete
h	Beam height
h_R	UHPC layer height
V_f	Volume fraction content
a	Shear span
d	Effective beam depth
RPC	Reactive powder concrete
RC	Reinforced concrete
P_u	Ultimate load
P_{cr}	First crack load