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SHEAR STRENGTH AND BEHAVIOR OF ULTRA-HIGH PERFORMANCE FIBER REINFORCED CONCRETE (UHPC) DEEP BEAMS WITHOUT WEB REINFORCEMENT

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ABSTRACT

Ultra-high performance fiber reinforced concrete (UHPC) is a new class of concrete that has been developed in recent decades, it has enhanced properties such as; very high compressive strength, improved tensile strength. In this study, three types of concrete were used based on the compressive strength of concrete, named; Normal Strength Concrete (NSC) of ($f'_c = 42$ MPa), High Strength Concrete (HSC) of ($f'_c = 63.75$ MPa) and Ultra High Performance Concrete (UHPC) of ($f'_c = 134.5$ MPa).The experimental program included casting and testing of fifteen reinforced concrete deep beams without web reinforcement (stirrups), nine specimens of (UHPC), three specimens of (HSC) and three specimens of (NSC), in order to study the shear strength and behavior of deep beams under two point loading. Considered variables were; the compressive strength of concrete (42, 63.75 and 134.5 MPa), the shear span to depth ratio (a/d) (1, 1.5 and 2) and over all depth of the beam (h) (180, 240 and 300 mm), while the width of all beams was (120 mm). The experimental results showed that the compressive strength of concrete also the shear span to depth ratio (a/d) has a significant effect on failure load, while the increase in overall depth of the beam from (180 to 240) mm reduces the nominal shear stress significantly, but beyond which no obvious size effect can be seen.

KEYWORDS: Shear Strength, Ultra-High Performance Fiber Reinforced Concrete (UHPC), Deep Beams

INTRODUCTION

Reinforced concrete deep beams are used as load distributing structural elements such as transfer girders, pile caps, foundation walls, and offshore structures. The shear strength evaluation of reinforced concrete beams has been the subject of several studies devoted to determine the influence of the main parameters.

Due to the small value of span-depth ratio, the strength of deep beams usually controlled by shear strength rather than flexural strength, if normal amounts of longitudinal reinforcement are used.[1,2]

According to ACI 318-11[3] deep beams are defined as members loaded on one face and supported on the opposite face, so that compression struts can develop between the loads and the supports. Moreover, deep beams have either:

- $(\frac{l_n}{h}) \leq 4.0$; or *(for distributed load case)*
- $(\frac{a}{d}) \leq 2.0$ *(for points load case)*

Shear force presents in beams at sections where there are a change in bending moment along the span, it is equal to the rate of change of bending moment. Several experimental studies have been conducted to understand the various modes of failure that could occur due to possible combination of shear and bending moment acting at a given section. The main obstacle to the shear problem is the large number of parameters involved.[4,5]

UHPC consists of fine sand, cement, silica fume and quartz flour in a dense, low-water cementitious materials ratio (0.15 to 0.19) mix. Compressive strengths of (124- 206) MPa can be achieved depending on the mixing and curing process, and it has tensile strengths of 6.3 to 11.9 MPa. The material has low permeability and high durability, to improve ductility, steel fibers are added.[6]

OBJECTIVES

The main objectives of this research can be summarized below:

- To study the shear strength and behavior of UHPC simply supported deep beams without web reinforcement under two points loads such as; (crack pattern, central deflection, support rotation, type of failure and strains in concrete and longitudinal reinforcement.
- To investigate the effect of compressive strength of concrete, shear span to depth (a/d) ratio and size effects on the shear strength and behavior of UHPC deep beams without web reinforcement.

EXPERIMENTAL PROGRAM

The experimental program included casting and testing of fifteen reinforced concrete deep beams without web reinforcement in which nine specimens were (UHPC), three were (HSC) and three were (NSC). The considered variables were; the compressive strength of concrete (f'_c), the shear span to depth ratio (a/d) and over all depth of beam (h).

Materials

Cement: The cement used in this study was Ordinary Portland Cement (CEM-I 42.5R).

Silica Fume: The smallest particle, the silica fume, has a diameter small enough to fill the interstitial voids between the cement particles.

Fine Aggregate (Sand): The sand was well washed and air dried and separated according the standard set of sieves, after that, the sieves remixed in to two types of grades meeting the standard limitations of ASTM C33, the grade of sand used for (UHPC) was different from that for (HSC and NSC).

Coarse Aggregates (Gravel): Two types of coarse aggregates were used in the investigation. Natural river gravel with maximum size of (12.5) mm were used for (HSC and NSC), and crushed Granite rocks with maximum size of (9.5) mm were used as coarse aggregate for (UHPC).

Superplasticizer: A high dosage of Superplasticizer was used to obtain workable UHPC mixes with very low water-to-cement ratio (w/c).

Water: In all mixes for all types of concretes, curing and washing, tap water was used. It was clean and free from injurious.

Steel Fibers: The steel fibers used in this study were straight steel wire fibers (un-deformed). The fibers have aspect ratio (l/d) of (80), a nominal diameter of 0.2 mm and a nominal length of 40 mm.

Reinforcing Steel: Deformed steel bars were used in the longitudinal reinforcement with various bars diameters (10, 12, 16, 20 and 25 mm) in order to satisfy the specific longitudinal reinforcement ratio (ρ_w).

MIX PROPORTIONS

The main variable in this study is compressive strength of concrete (f'_c), three types of concrete mixes were used; Ultra-High Performance Concrete (UHPC), High Strength Concrete (HSC) and Normal Strength Concrete (NSC). Two trial mixes were done for (HSC) and two trials for (NSC), while (9) trials were performed for (UHPC) in which the proportions of materials were varied. Table (1) shows the mix proportions for (HSC, NSC and 4 mixes for UHPC). Six samples of (150*150*150) mm cubes of concrete were casted for each trial mix for HSC and NSC, while six (100*100*100) mm were casted for UHPC, three samples were tested at age 7 and 28 days.

Table 1: Trial Mixes ($(\mathrm{K_g})$ per $(\mathrm{m^3})$ of Concrete)

Type of Concrete	Trial Mix No.	S	G	B		SP (% of wt. of B)	ST (V_f)	W (W/C)
				C	SF			
NSC	1	821	821	410				192.7 (0.47)
	2*	800	800	390				201 (0.515)
HSC	1	634	1085	555		5.5 (1%)		171 (0.308)
	2*	634	1085	540		5.5 (1%)		166.8 (0.307)
UHPC	1	550	750	945	150	34 (3.1 %)	35 (0.4)	217.4 (0.23)
	2	600	600	950	180	43 (3.8 %)	31.2 (0.4)	199.5 (0.21)
	3	800	400	830	200	39 (3.8 %)	39 (0.5)	174.3 (0.21)
	4*	800	400	830	200	39.14 (3.8%)	31.2 (0.4)	182.6 (0.22)

Where;

* The selected mixes for casting the specimens.

C: Cement, **S:** Sand, **G:** Gravel, **W:** Water,

SF: Silica Fume, **SP:** Superplasticizer, **ST:** Steel fiber,

W/C: Water-to-Cement Ratio, **B:** Binders, V_f: Volume fraction

BATCHING, MIXING AND CASTING PROCESS

6.1 Batching; this process was done by prepare the mixture compounds through taking the specific weights depend on size of the mix, a sample of Batching process is shown in Figure (1).

Figure 1: Batching Process

6.2 Mixing; the mixing process for (UHPC) takes additional time compare to conventional concrete, this is mainly due to very low (w/c) ratio. The overall mixing time for (UHPC) is about 30 minutes. The mixing process can be illustrated in the following steps:

- Feeding the fine and coarse aggregate in mixer and mix for 1 minute.
- Add some water to the premix for absorption purpose and mixing for 1 minute, then wait 3 minutes.
- Add the binders (cement and silica fume) to the premix and mixing for 2 minutes.
- Add half of superplasticizer to mixing water.
- Add water (with half of superplasticizer) to premix slowly over 2 minutes.
- Wait 1 minute, and then add remaining superplasticizer to premix.
- Continue mixing as the UHPC changes from a dry powder to a thick paste. This process takes about 15 minutes and it is may vary.
- Add fibers to the mix slowly over the course of 5 minutes.
- After the fibers have been added, continue running mixer for 2 minutes to ensure that the fibers are well dispersed.

6.3 Casting; the molds were already put in a horizontal manner on the vibrating table, the inside face were oiled, the strain gages fixed on the mid space of steel bars and placed inside the molds and fixed properly. Three specimens (beams) with different geometry and same concrete type with six cubes, three cylinders and three prisms were casted just after mixing process was completed. The casting process was done by placing the concrete inside the molds in three layers and each layer was vibrated four about 1 minute for both types (HSC and NSC), while for (UHPC) the vibration time for each layer was 3 minutes due to the high consistency. At end of the third layer, the concrete surface was finished and leveled by a steel trowel. The casting and testing direction of beams was the same direction, the casting details is shown in Figure (2).

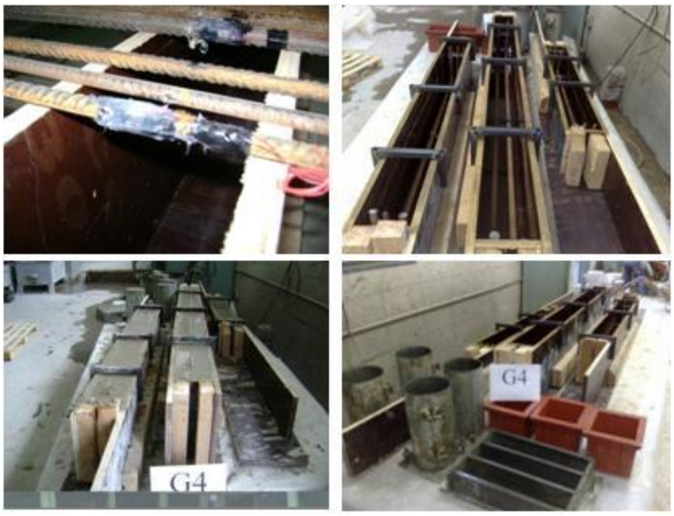

Figure 2: Details of Casting Process

SPECIMEN DETAILS

Fifteen specimens (Deep Beams) were cast and tested up to failure divided into five groups (G1 to G5) to investigate the effects of three variables on shear strength of deep beams which are:

- Compressive strength of concrete
  - Normal Strength Concrete (NSC). ($f'_c = 42\ MPa$)
  - High Strength Concrete (HSC). ($f'_c = 63.75\ MPa$)
  - Ultra-High Performance Concrete (UHPC). ($f'_c = 134.5\ MPa$)
- The shear span to depth ratio (a/d). (1, 1.5, 2)
- The overall depth of the beams (h). (0.18, 0.24, 0.3) m.

Table 2: Detail of Tested Beams

G. No.	Name of Specimen	b (mm)	h (mm)	d (mm)	(h/b) Ratio	(a/d) Ratio	f'_c (MPa)	**(A_s)act mm^2	+$\rho_{act.}$	$\rho_{max.}$
G1	B181U	120	180	150	1.5	1	134.5	706 [2Ø20+1Ø10]	0.039	0.078
	*B1815U					1.5		706 [2Ø20+1Ø10]		
	B182U					2		706 [2Ø20+1Ø10]		
G2	B241U		240	210	2	1		980 [2Ø25]	0.039	0.078
	B2415U					1.5		980 [2Ø25]		
	B242U					2		980 [2Ø25]		
G3	B301U		300	270	2.5	1		1294 [2Ø25+1Ø20]	0.04	0.078
	B3015U					1.5		1294 [2Ø25+1Ø20]		
	B302U					2		1294 [2Ø25+1Ø20]		
G4	B181H		180	150	1.5	1	63.75	339 [3Ø12]	0.0188	0.039
	B2415H		240	210	2	1.5	63.75	480 [2Ø16+1Ø10]	0.019	
	B302H		300	270	2.5	2	63.75	628 [2Ø20]	0.0194	
G5	B181N		180	150	1.5	1	42	304 [2Ø12+1Ø10]	0.0168	0.029
	B2415N		240	210	2	1.5	42	402 [2Ø16]	0.0159	
	B302N		300	270	2.5	2	42	480 [2Ø16+1Ø10]	0.0148	

* “B1815U”, Define as [“Beam”, h= “18 cm”, a/d= “1.5”, concrete type = “UHPC”]
** (A_s) act; provided steel area was enlarged to avoid flexural failure.
\+ $\rho_{act.}$; set as half of $\rho_{max.}$

TESTING PROCEDURE

Especial arrangement were made through putting steel plate at loading and supporting locations and center the beam under the loading point and dividing it by stiff steel beam. The locations of loading and supporting, concrete strain gage, inclinometer and dial gage were appointed as shown in typical sketch in Figure (3), at time of starting the loading process, all indicators were adjusted. The load was increased gradually of range 20 and 50 kN for (NSC and HSC) and (UHPC) respectively. At each increment of loading, up to failure, the steel and concrete strain gages, dial gage and inclinometer were recorded.

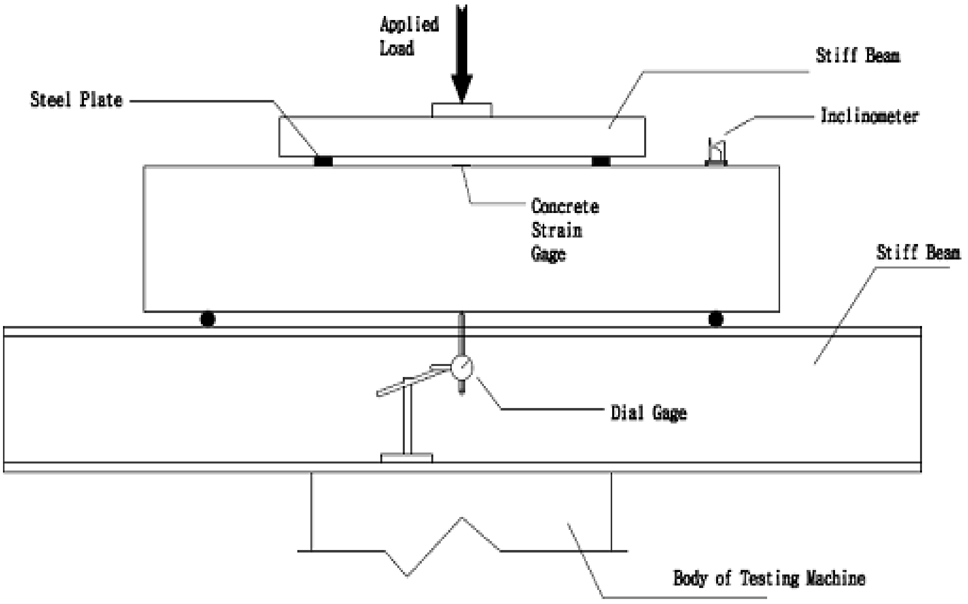

Figure 3: Typical Sketch for Tested Beams

RESULTS AND DISCUSSIONS

Control Specimens

Table 3: Mechanical Properties of Control Specimens

Group No.	Name of Specimen	Type of Concrete	f_{cu} MPa	f'_c MPa	f_{ct} MPa
G1	B181U	UHPC	134.5	134.5	7.48
	B1815U				
	B182U				
G2	B241U				
	B2415U				
	B242U				
G3	B301U				
	B3015U				
	B302U				
G4	B181H	HSC	75	63.75	4.85
	B2415H				
	B302H				
G5	B181N	NSC	52.5	42	2.55
	B2415N				
	B302N				

Reinforced Concrete Deep Beams

Load-Deflection Relationships

The first three groups of relationships are shown in Figures. (4, 5 and 6) in which for each group the beams have the same compressive strength and height while have different (a/d) ratios. It can be noted that the ductility of beams increases by increasing (a/d) ratio from (1 to 2) which lead to increasing the moment over the span.

Generally the curves can be divided into two stages; the first stage is elastic (linear stage) in which no flexural or shear cracks appear, after increase the load, the beam becomes in second stage that is inelastic (non-linear stage) in which the flexural cracks are noticed, in these relationships it can be seen that the slope of curve at stage one is steeper than of second stage. The separation between these two stages is more pronounced for higher (a/d) ratios such as (B1815U and B302U).

At a specific applied load in second stage, the central deflection of beams B181H, B2415H and B302H are 100%, 130% and 100% greater than B181U, B2415U and B302U respectively while the deflection of beams B181N, B2415N and B302N are 180%, 145% and 150% greater than B181U, B2415U and B302U respectively as shown in Figures (7, 8 and 9). The reason is the relationship between the deflection and the modulus of elasticity of concrete (including the compressive strength), viz, when the compressive strength of concrete increased from NSC to HSC then to UHPC lead to decreasing the central deflection of beams, also the high longitudinal reinforcement ratios used in this study. While at first stage of load-deflection relationships, the above variation is not pronounced.

The effects of beams height can be noticed in Figures (4, 5 and 6) in which at a specific applied load for a beam of the same compressive strength and (a/d) ratio with changing the height from 180mm to 240 mm then to 300 mm (increase the moment of inertia of beam section) lead to decrease in central deflection of the beam.

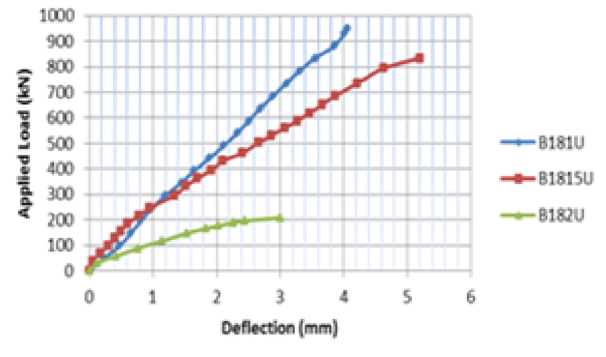

Figure 4: Load-Deflection Curves for G1

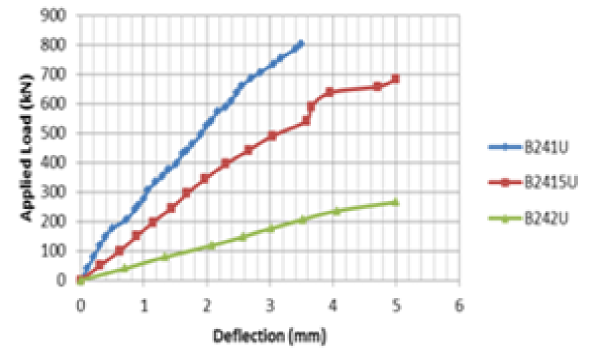

Figure 5: Load-Deflection Curves for G2

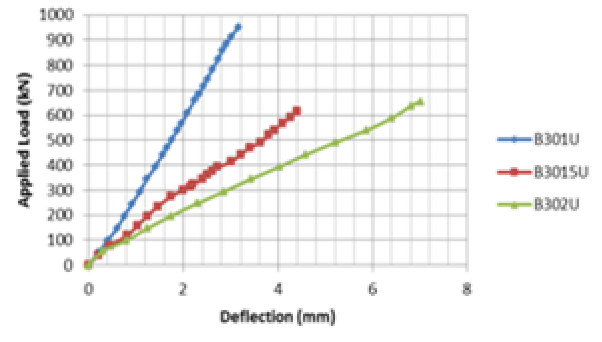

Figure 6: Load-Deflection Curves for G3

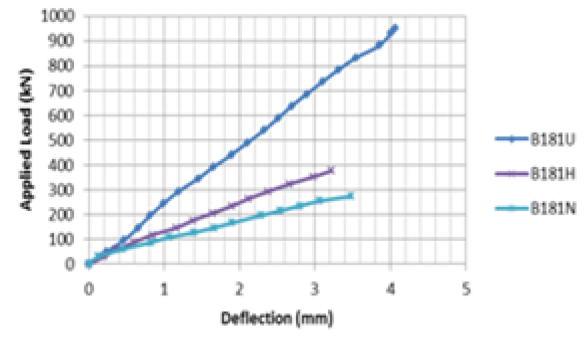

Figure 7: Load-Deflection Curves for Different Compressive Strength

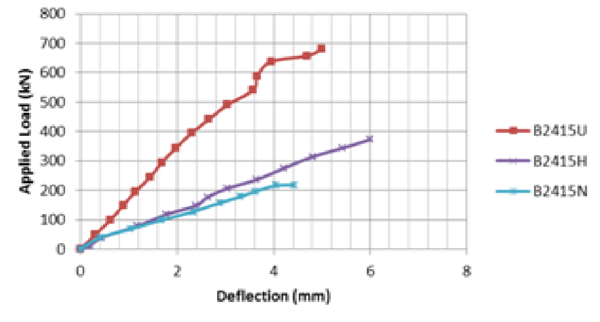

Figure 8: Load-Deflection Curves for Different Compressive Strength

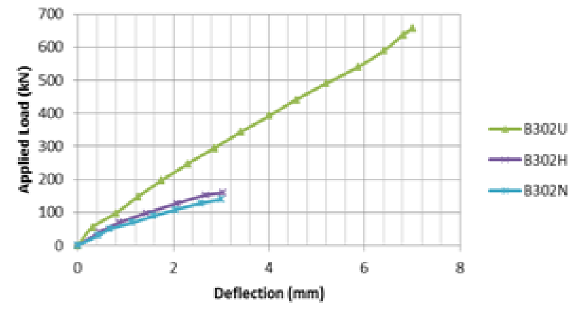

Figure 9: Load-Deflection Curves for Different Compressive Strength

Load-Concrete Strain Relationships

The load-top mid span concrete strain relationships are listed in Figures (10 Up to 15), it can be seen that the curves behave similarly to load-deflection curves. The maximum value of concrete strain at compression zone obtained from test results of all beams was 0.00223 that is lower than the ultimate strain of concrete under compression at which the crushing occurs that is equal (0.003). Because of the very high compressive strength of (UHPC) compared to other conventional concrete, the difference in strain between NSC and HSC is lesser compared to the difference between HSC and UHPC as shown in Figures (13, 14 and 15).

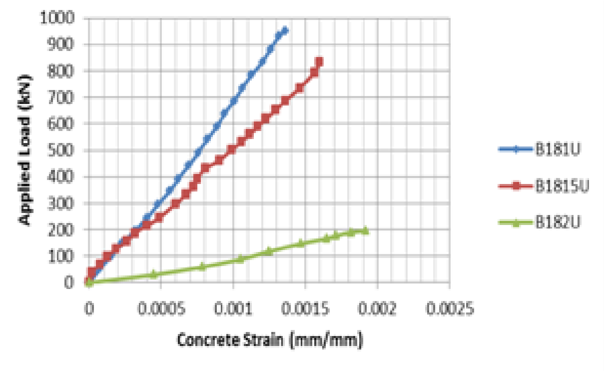

Figure 10: Load-Concrete Strain Curves for G1

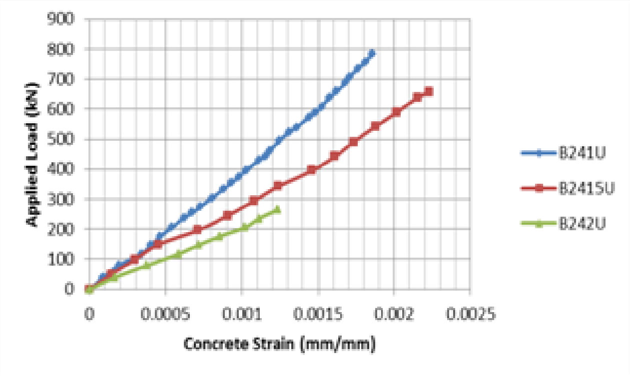

Figure 11: Load-Concrete Strain Curves for G2

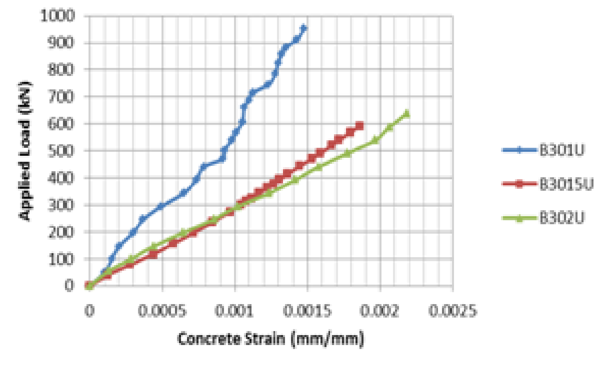

Figure 12: Load-Concrete Strain Curves for G3

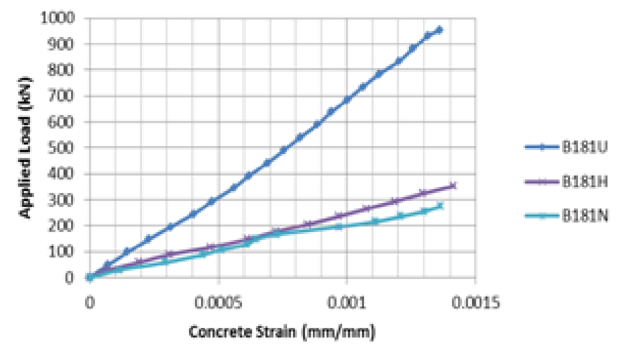

Figure 13: Load-Concrete Strain Curves for Different Compressive Strength

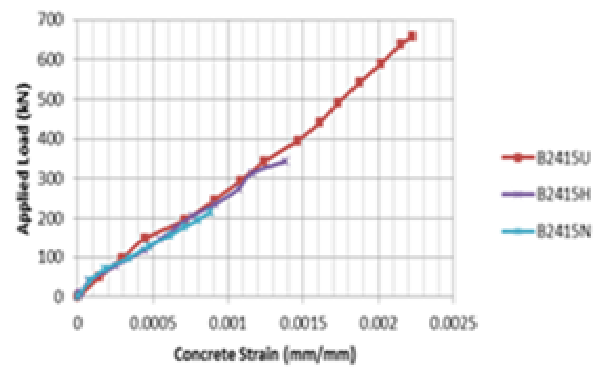

Figure 14: Load-Concrete Strain Curves for Different Compressive Strength

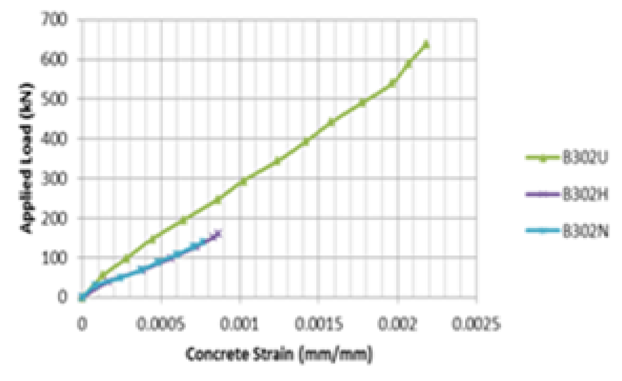

Figure 15: Load-Concrete Strain Curves for Different Compressive Strength

Specimens Behavior under Loading

Through testing process, the load was applied in increments and the behavior of beams was observed, the first flexural cracking load, first shear cracking load, failure load and the mode of failure were recorded and presented in Table (4).

Table 4: Results of Tested Deep Beams

Group No.	**Name of Beam**	**First Flexural Cracking Load (kN) *(Experimental)***	**First Shear Cracking Load (kN) *(Experimental)***	**Failure Load (kN) *(Experimental)***	**Nominal Shear Stress ($V^{TEST}/bd\sqrt{f'_c}$) MPa**	**Mode of Failure**
G1	B181U	294.2	346.2	> 951.3	2.3	True Shear (Splitting)
	B1815U	245.2	274.6	833.6	2.0	True Shear (Splitting)
	B182U	78.4	147.1	207.9	0.5	True Shear (Splitting)
G2	B241U	117.7	176.5	801.2	1.4	True Shear (Splitting)
	B2415U	196.1	343.2	681.6	1.2	True Shear (Splitting)
	B242U	78.5	147.1	264.8	0.5	Diagonal Tension
G3	B301U	245.2	245.2	> 951.3	1.3	True Shear (Splitting)
	B3015U	196.1	235.4	616.9	0.8	Diagonal Tension
	B302U	196.1	441.3	656.1	0.9	True Shear (Splitting)
G4	B181H	88.3	176.5	377.6	1.3	True Shear (Splitting)
	B2415H	88.2	147.1	372.7	0.9	True Shear (Splitting)
	B302H	68.7	127.5	159.9	0.3	Diagonal Tension
G5	B181N	88.3	107.9	275.6	1.2	True Shear (Splitting)
	B2415N	68.7	127.5	217.7	0.7	True Shear (Splitting)
	B302N	68.7	107.9	139.3	0.3	Diagonal Tension

Effect of Concrete Compressive Strength

The results in Table (4) shows that the concrete compressive strength has no obvious effects on the formation of first flexural cracks when the compressive strength increased from 42 MPa to 63.75 MPa, while the first flexural cracking load increased by 165% when it increased from 63.75 MPa to 134.5 MPa, the reason can be traced to the presence of steel fibers in UHPC matrix.

On the other hand the first shear cracking load increased by 31% and 150% when the compressive strength was increased from 42 MPa to 63.75 MPa and from 63.75 MPa to 134.5 MPa respectively.The ultimate (failure) load for tested deep beams was increased by increasing the compressive strength.

Generally the results showed that the failure load increased by 44% and 150% when the compressive strength was increased from 42 MPa to 63.75 MPa and from 63.75 MPa to 134.5 MPa respectively. Figures (16, 17 and 18) show the effects of concrete compressive strength on behavior of deep beams.

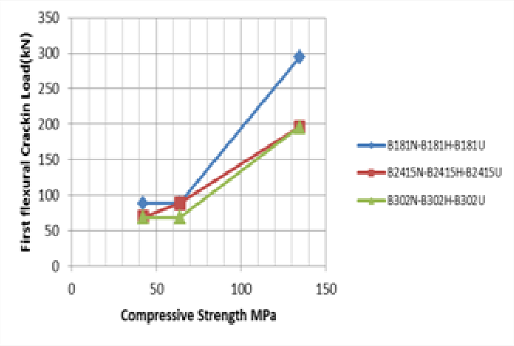

Figure 16: Effect of Concrete Strength on First Flexural Cracking Load

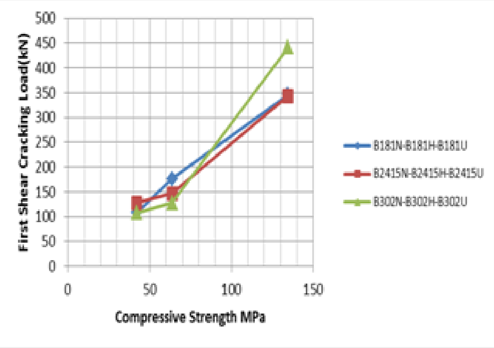

Figure 17: Effect of Concrete Strength on First Shear Cracking Load

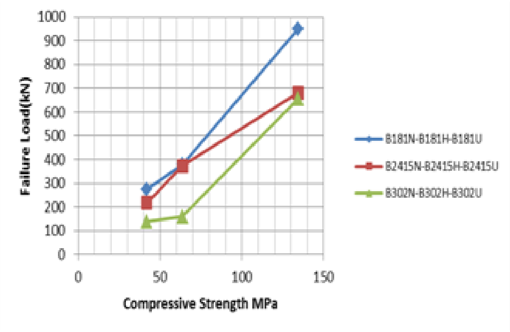

Figure 18: Effect of Concrete Strength on Failure Load

Effect of Shear Span to Depth Ratio

The results in Figure (19) showed that the failure load decreased by about 30% and 150% when (a/d) ratio increased from 1 to 1.5 and from 1.5 to 2 respectively, this means; the increasing of (a/d) ratios leads to a significant decreasing in ultimate load, but it can be seen in many previous researches studying the effects of (a/d) ratios on the behavior of deep beams, that this decreasing in failure load is limited beyond values of 2 or 2.5 for (a/d).[7]

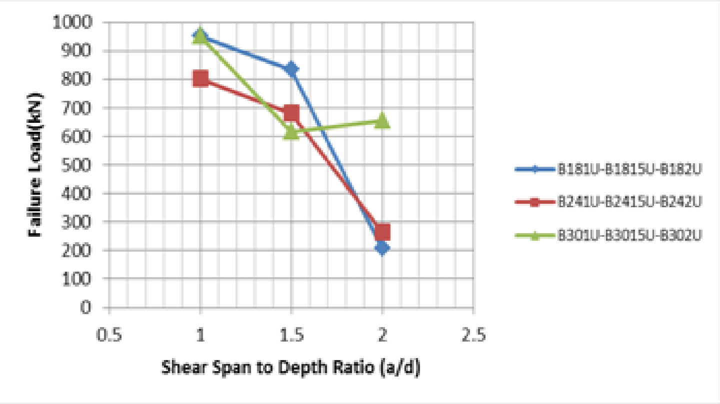

Figure 19: Effect of (a/d) on Failure Load

Effect of Beam Height

Since the beams have different heights and therefore different flexural stiffnesses (EI) and to investigate the size effect, the height of beams is plotted versus the shear stress $(V^{TEST}/bd\sqrt{f'_c})$ rather than the shear force. The size effect on first flexural, first diagonal and nominal shear stress is shown in Figure (20). The Figure shows that the effect of beam height is approximately negligible on flexural and diagonal shear cracks stresses, while its effect is more pronounced on nominal shear stress.

When the beam height increased from (180 to 240) mm a significant decreasing in nominal shear stress is noticed, after which no obvious reducing in nominal shear stress can be seen, this means that there is a significant size effect for beams having depth less than 240 mm.

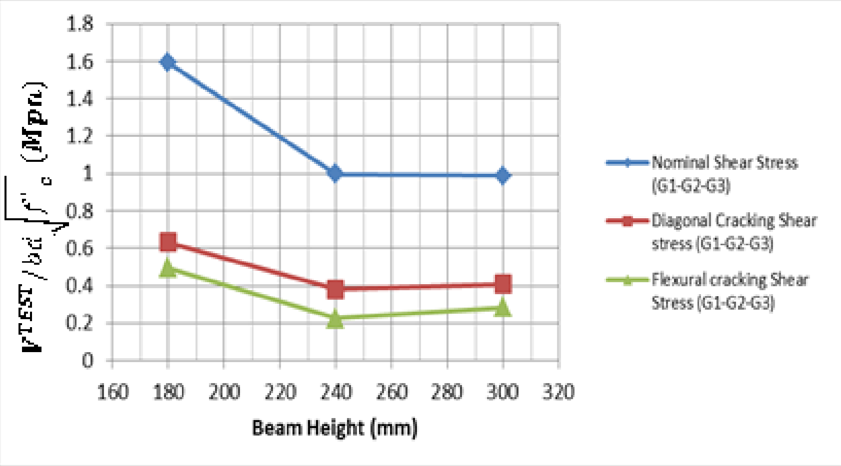

Figure 20: Size Effect Onshear Stress

CONCLUSIONS

- At a specific applied load after generation of flexural cracks, the central deflection of beams decreased by 155% and 110% by increasing the compressive strength of concrete from 42 to 134.5 and from 63.75 to 134.5 respectively.
- By increasing the compressive strength of concrete from 42 to 63.75 then to 134.5, the diagonal cracking load increased by 31% and 150% respectively. The failure load is increased by about 44% and 150% when the compressive strength of concrete increased from 42 to 63.75 then to 134.5 respectively.
- The shear span to depth ratio (a/d) has high significant effect on failure load, it can be seen that by increasing (a/d) ratio from 1 to 1.5 then to 2, lead to decreasing the failure load by 30% and 150% respectively. However, as can be noted from many previous researches that this effect is limited beyond (a/d) value of 2 or 2.5.
- (a/d) ratios has small effect on formation the first flexural cracks, while the ratio of first diagonal cracking load to failure load is 28%, 41% and 64% for (a/d) ratios of 1,1.5 and 2 respectively.
- When the beam height increased from (180 to 240) mm a significant decreasing in nominal shear stress can be seen, after which no obvious reducing in nominal shear stress was noticed. The size effect is more pronounced on the nominal shear stress rather than first flexural and diagonal cracking shear stress.
- The flexural cracks formation occurs at about 30% of failure load, while the diagonal cracks occur at 45% of failure load and forms suddenly.

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