Punching Shear Strength of Ultra-High Performance Concrete Flat Slabs

Mahmoud Abdelfattah, Ayman Hussein Khalil, Ebtisam Abd Alaziz, Ezz Eldin Mostafa

Abstract—Not for a long time, there is growing interest in a new generation of concrete to make huge development in construction. A relatively new sophisticated construction material of cementations complex, ultra-high performance concrete (UHPC). The UHPC refers to a mighty generation of concrete whose compressive strength more than 150MPa, tensile strength greater than 5MPa. The benefits of UHPC is perceived as a revolutionary material that has high compressive strength, self-compacting, and ductile behavior. However, the UHPC is still limited to a few structural applications due to high cost, limited design codes, and the high factors of safety adopted in design. This paper describes the mixing design and procedures for UHPC and obtained experimental results that proposed an increase in information of slab-column connections against punching shear failure. The punching shear test of flat plate slab depends mainly on the tensile strength, fabrication method, and local synthesis. The experimental method was examined a punching shear strength of UHPC flat plates having dimensions 1350*1350*80mm. The test is performed under vertical loading, using various parameters on the punching shear strength. These parameters include concrete strength, column shape, column aspect ratio, and reinforcement ratio. The experimental setup is hydraulic press allows investigating the concrete shear strength under quasi-static loading regime.

Index Terms— Cracking pattern, Deflection, Flat plates, Experimental study, Interior column, Punching shear, Steel fibers, Ultra-High Performance Concrete (UHPC).

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1 Introduction

Reinforcement concrete flat plate structure is widely used nowadays due to the vast advantages such as formwork is simplified, decrease floor heights in buildings, and its pleasant appearance. The slabs without column capitals or drop panels appeared in the 1950s[1].

However, the critical problem of this system is the failure region of column-slab connections known as punching shear failure. A punching shear failure means the column is essentially pushed through the slab due to the high stresses region of column-slab connections. The engineering designer must consider punching shear failure in a flat plate system which can become an increasingly critical section in the whole system that occurs suddenly without any warning. The failure of one joint in the system may lead to loss of structural solidity.

Recently, Designers are looking forward to increasing concrete compressive strength in a structure because it is one of the most effective methods to avoid punching shear failure. Besides, the increasing concrete compressive strength in a structure minimizes the deflections under load particularly with long spans, improves long-term properties, decrease the cross-section of the member with the same strength capacity and decrease the total weight of the structure that helps in earthquake resistance especially in a tall building that located in earthquakes zones.

This study was applied UHPC to increase concrete compressive strength. The UHPC has been demonstrated to have compressive strengths more than seven times and tensile strengths greater than three times that of conventional concrete[2].

Interesting is, that UHPC exhibits nearly linear behavior up to 90% of its compressive strength before diverging 5 % from linear elastic behavior (this value is 45 % for NSC)[3].

Investigated was punched four interior column slab connections are made of UHPC. The column aspect ratio, column shape, and flexural reinforcement ratio in slabs are chosen as test parametric. In the Concrete Research laboratory - Faculty of Engineering, Ain Shams University – Cairo – Egypt were made the experimental test.

2 UHPC Specimens and Set Up

The immense mechanical and durability properties of UHPC make all the world interesting and researching merely with different names. Various brand names are used to refer to cementitious composite materials with ultra-high compressive strength and improvement durability around the world like [4, 5] Ductal® is a common name in the USA, Ultra-High Performance Concrete(UHPC) prevalent in Europe, while Reactive Powder Concrete(RPC) rife in Asia. Also, there are common names around the world as Compact Reinforced Composite (CRC), Densified Small-Particle(DSP) concrete, Fiber-Reinforced High-Performance Concrete (FRHPC), Macro Defect-Free(MDF) concrete, Multi-Scale Fiber-Reinforced Concrete (MSFRC), Steel Fibrous Cement-Based Composite(SFCBC).

2.1 UHPC Material

Ultra-high performance concrete (UHPC) is a new generation of concrete imperturbable of very fine powder as portland

- **Mahmoud Abdelfattah** *Construction & Building Engineering, Faculty of Engineering & Technology, Arabic Academy for Science and Technology, Egypt, E-mail: m.abdel.fattah@outlook.com*
- **Ayman Hussein Khalil** *Structural Engineering Department, Faculty of Engineering, Ain Shams University, Egypt, E-mail: ayman@adec-arabia.com*
- **Ebtisam Abd Alaziz** *Structural Engineering Department, Faculty of Engineering, Arabic Academy for Science and Technology, Egypt, E-mail: Eyehia16@gmail.com*
- **Ezz Eldin Mostafa** *Structural Engineering Department, Faculty of Engineering, Ain Shams University, Egypt, E-mail: Ezzeldin.mostafa@eng.asu.eg*

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cement, fine sand, quartz sand, silica fume, superplasticizer, micro steel fiber, and water. In UHPC, the large particle used was micro steel fiber which made all courses were fine particles and all had mostly the same size that inspired UHPC densely packed concrete. Also, UHPC is self-compacting concrete in the fresh state that can flow under its weight and does not require external vibration.

Portland Cement

The portland cement is the most widespread material used around the world as a basic ingredient of concrete, mortar, stucco, and specialty grout. It is a fine powder, produced by heating limestone and clay minerals in a kiln to form clinker, and adding 2 to 3 percent of gypsum. Particle sizes of portland cement are ground slightly finer to a rather narrow range varying from 1µm to about 80µm, with a mean size of the order is 9 to 10µm. In UHPC was used CEM I 52.5N contain low C3A required low water demand and concerning the risk of secondary ettringite formalization in concrete influenced by different failure mechanisms alkali, silica reaction [ASR]. And, at the same time, saving the concrete from freezing and thawing [FT], and wetting and drying [WD] in sulfate.

UHPC used approximately twice the amount of cement as a conventional concrete normally lies between 600 to 1000kg/m^3 up to 28.5 mass-% with a fineness of the cement between 3000 and 4500 cm^2/kg as shown in Fig. 1(A).

Silica Fume

The silica fume is a pozzolanic material also known as micro silica, which is a non-crystalline polymorph of silicon dioxide and silica. It is fine powder generates from the gases escaping from the product of the furnace of silicon metal and ferrosilicon alloy that contains spherical particles with mean particle size is 0.1 to 0.2 µm. In UHPC, it was very useful to used gray silica fume that has ultra-fine partial that can replace the water space voids on cement paste binder, and increase the workability see Fig. 1(B). Also, silica fume reacts with calcium hydroxide (CH), which produces from portland cement hydration that produces more of the CSH binder. When CH is replaced by CSH, which has much higher strength, and porosity decreases in the bulk. The quantity uses in UHPC about 10-40 % of the cement mass.

Fine Sand

The fine sand is the largest particle in the UHPC dry premix. Generally, particle sizes between 150 to 600µm can be seen from Fig. 1(C). So the sand was used in UHPC sieving gently and take particle that passing from sieve number 30 and retained on sieve number 100. The sand helps in add more volume to the concrete that called filling material, reduces the amount of water demand in mixing, prevents excessive shrinkage, hair cracks, makes smooth surfaces that help in finishing the top surface. Besides all previous benefits, it is an economy that has a very low price comparing with other partials.

Quartz Powder

The quartz is available in natural as crystalline form, while the quartz was crushed to make quartz powder with particle size range 10 to 45µm appearance as Fig. 1(D). Quartz powder has many common names like quartz flour, ground quartz, crushed quartz, silica sand, quartz sand, and quartz flower. Quartz powder is inert filler partials that have a high percentage of silica with white color. The main function of quartz is giving maximum resistance to the concrete against heat and decrease heat exposed during the reaction in a fresh green state that prevents dry shrinkage and hair cracks in concrete.

Superplasticizer

The superplasticizer (SP) is a chemical complex that enables the outcome of concrete with less water content also common name is High Range Water Reducers (HRWR). SP are additives used to make concrete high workability without segregation, early strength, full flow action, and reduces the need for the vibrator. The mean function of a superplasticizer is high decrease the water-cement ratio, decrease porosity, and also to improve the workability of concrete. In UHPC only used third-generation plasticizers of Poly Carboxylate Ethers (PCE) due to saving flow of concrete with a very low water-binding ratio as showing in Fig. 1(E). The large quantity of superplasticizer uses in UHPC which up to 2 % of cement mass in order to obtain acceptable workability.

TABLE 1
MATRIX MIX PROPORTION

Composition	Quantity
Cement CEM 52.5N **[kg/m^3]**	730
Silica fume (0.1-0.2 µm) **[kg/m^3]**	235
Sand (0.15-0.6 mm) **[kg/m^3]**	885
Quartz Powder (10-45 µm) **[kg/m^3]**	220
Superplasticizer **[kg/m^3]**	20.075
(Third-generation)	**[2.75% by weight of cement]**
Steel fibers **[kg/m^3]**	156
(L=13mm, D=0.2mm)	**[2% by concrete volume]**
Water **[Liter]**	164.05
Water/Binder ratio (w/b)	17%

Steel Fibers

The steel fibers are one of the most important particles to produce UHPC which enhances the ductility of concrete, in both tension and compression loading, gives high flexural strength to concrete. Also, UHPC was an excellent performance in abrasion resistance, and increase the ability to energy absorption during impact load. The steel fibers irregularly distributed randomly in concrete to that makes crack pattern distributed and not uniform lead to decreases in the width of the cracks and severs in the composite while the workability of concrete decreases. With about 1 percent fiber volume, the increase in ultimate load amounted to about 40%, and deflec-

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tions are reduced by 30%, and tension steel strain, compression concrete strain, and rotation by 40-50%[6]. The optimum fiber content was found to be 3% of 6mm or 2% of 13mm[7]. In UHPC was used micro straight circular steel fibers knowing as micro steel fibers. The specification was low carbon steel fiber, length of 13mm, a diameter between 0.2-0.25mm with aspect ratio 65, tensile strength ≥ 2800MPa, and meets specification: ISO9001, CE: 2008. It had a shape with copper-coated golden and bright appearance in Fig. 1(F).

Many trials were made to develop an adequate concrete mix with required strength values. Sometimes changed in composite type and the weights. Also, some time changed in mixing procedures and mixing machines. Finally, the preferable mix design was fetched and detailed in **TABLE 1**. The same compound but without micro steel fibers, the result was high strength concrete (HSC) with average compression strength 70MPa. While was decided UHPC with micro steel fibers mix design with the total weight dry premix 2070kg/m^3.

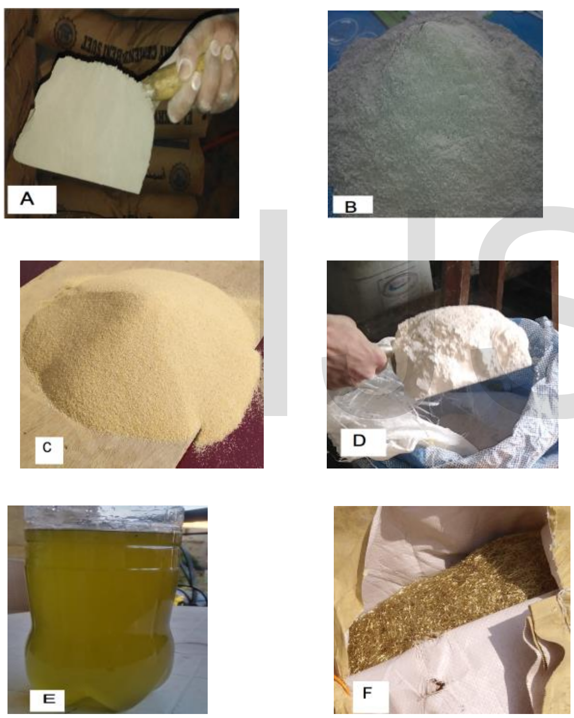

Fig. 1 UHPC constitute
(A) Portland cement (B) Silica fume (C) Sand (D) Quartz powders (E) Superplasticizer (F) Micro steel fibers

2.2 Specimen Instrumentation

A small slab measurements instrument were used like reinforcement strain gauges, concrete strain gauges, and linear variable differential transducers (LVDTs) are monitoring the behavior of the specimens during loading. All instrument was connected to a computerized data acquisition system (DAQ) to record the readings of reinforcement strain, concrete strain, and specimen deflection.

Electric resistance tension gauge was fixed and glued to the flexure reinforcement before pouring concrete while at the compression side of concrete was put after pouring and painting concrete. The four LVDTs were used to measure the vertical displacement at various locations. The location of the LVDT and strain gauge is detailed in Fig. 2.

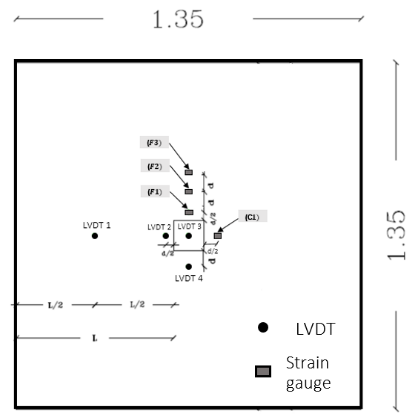

Fig. 2 Instrumentation details.

2.3 Mixing Procedures

There is a change in procedures and techniques for mixing UHPC simply different than traditional concrete mixing. The procedures and techniques are:

A. Use a piece of wet fabric to clean carefully the pan mixer.
B. Weigh all constituent materials then add half superplasticizer to the water.
C. Place quartz, silica fume, and sand in pan mixer then mix for 2 minutes drying as shown in Fig. 3(A).
D. Place cement into dry premix in the pan mixer and leave mixing 2 minutes drying too.
E. Add water with half of the superplasticizer to premix slowly for the course of 3 minutes as shown in Fig. 3(B).
F. Wait 1 minute, then add the remaining half superplasticizer to premix for the course of 30 seconds.
G. Continue mixing as the UHPC changes from a dry powder to a thick paste for approximately 7 minutes. In this step amazing happen the powder change suddenly to the past without an increased quantity of water as shown in Fig. 3(C).
H. Finally, add steel fibers to the mix slowly for the course for 2 minutes.
I. After the fibers have been added, continue running mixer for 1 minute to ensure the fibers are well homogenous with all compounds.
J. The maximum time to pouring concrete in formwork after finishing mixing is 25 minutes.

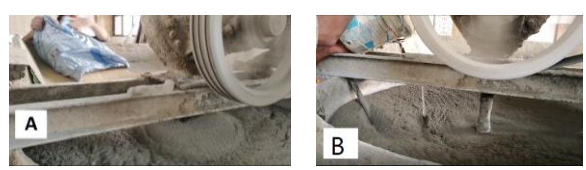

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Fig. 3 Mixing procedures and techniques.

2.4 Strengthening Procedure

The specimens were tested in an upside-down position concerning the position of a real structure as illustrates in Fig. 4. The specimens were lifted by crane hook and put on heavy steel I-beam frame arrangement with four edges. The I-beam was very rigid to not exhibit any deformation under the applied actuator load. A rubber mat of 1cm thickness and 10cm width was provided under the slab where necessary to ensure uniform contact along with the supports and to avoid the concrete edges splitting.

Summarizes the four specimens slabs in Table 2 according to slabs dimensions, thickness, and the number of steel bars in the middles and at both sides. It also contains column dimensions, the aspect ratio of columns, and expected load failure. Perceive the steel ratio at the middle of slabs is very huge because considering the uncertainty of the estimation of flexural and punching strength, to guarantee punching before flexural failure in the test, the estimated flexural strength should be at least 180% of the estimated punching strength by ACI punching shear formula[8] "(1)".

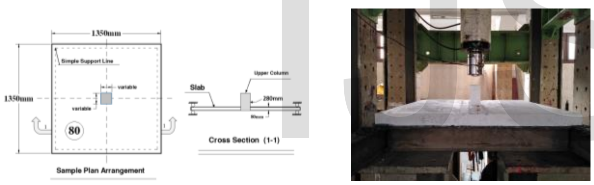


Fig. 4 UHPC Specimen Configuration.

TABLE 2
EXPECTATION DESIGN FOR SPECIMENS

Specimen	Slab Dimension, (mm)	Slab thickness, ts (mm)	Column dimension, a*b (mm)	The aspect ratio of column β	Expected load failure, (KN)	Steel bars on a slab at middle for 650mm		Steel bars on a slab at both sides for 350mm	
						Steel numbers	Steel ratio %	Steel numbers	Steel ratio %
SB1	1350*1350	80	100*150	1.5	191.03	9 Ø 18	4.40	4 Ø 12	1.614
SB2	1350*1350	80	100*130	1.3	180.7	7 Ø 18	3.425	4 Ø 12	1.614
SB3	1350*1350	80	120*120	1	185.87	7 Ø 18	3.425	4 Ø 12	1.614
SB4	1350*1350	80	150	——	170.38	7 Ø 18	3.425	4 Ø 12	1.614

$$V_C = 0.33\,\lambda\sqrt{f_c'}\; b_0\, d\sqrt{f_c'} \qquad (1)$$

3 EXPERIMENTAL RESULTS

The four specimens suffered from punching shear failure with no signs of flexural reinforcement yielding. The failure was characterized by a severe drop in the vertical load when the column along with a conical portion of the slab punched through the remainder of the slab as shown in Fig. 5. They have shown slight differences in the cracking pattern and the punching shear cone resulted in signs of initial flexure cracks.

The test result summarizes the experiment work in Table 3. The increase of concrete strength will be made a high increase in the load-deflection curve. As a clear show, SB1 and SB4 was the highest value of the load-deflection curve than other specimens as shown in Fig. 7. The load-defection of SB1 difference from other specimens by 22.7%, while for load-deflection of SB4 by a difference 11.4%. SB2 had the largest fracture deflection point value than other specimens a difference of 19.3%. The huge difference between the compressive strength of SB1 and the other specimen due to decreasing the quantity of water in the mixing design of SB1. The average difference between the analytical study result and the experimental result was 26.07%. So that the codes and guides book is more conservative and tory.

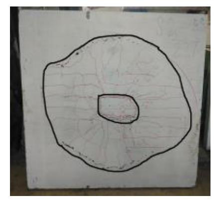
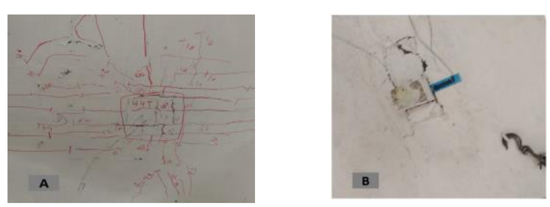


Fig. 5 Crack pattern at failure mode.

TABLE 3
SUMMARY OF TEST RESULT

Specimen ID	Concrete strength F_{cu} (MPa)	Analytical Expected load (KN)	Experimental Ultimate load (KN)	Experimental Deflection (mm)	P_{Ana}/P_{Expe} Ultimate load	Failure mode Ultimate load
SB1	238	307.675	445.51	22.6	0.69	Punching Failure
SB2	204	172.081	220.21	16.15	0.78	Punching Failure
SB3	210	185.87	236.31	15.88	0.7865	Punching Failure
SB4	214	192.76	275.35	20.5	0.70	Punching Failure
		Average			0.74	

As expected for UHPC, the presence of micro steel fiber in the specimens much higher value between a load value at appearance cracks and ultimate load about 81% difference. Also, a massive difference between cracks deflection, ultimate deflection, and fracture deflection. The difference between the deflection value at appearance cracks and ultimate deflection value about 67.5% and the difference between ultimate deflection value and fracture deflection value about 58% while the difference between the deflection value at appearance cracks and fracture deflection value about 86.75%.



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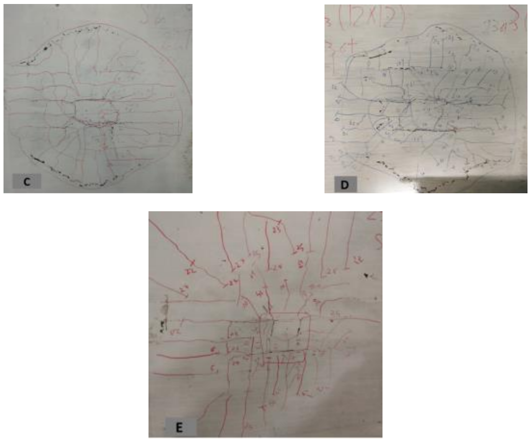
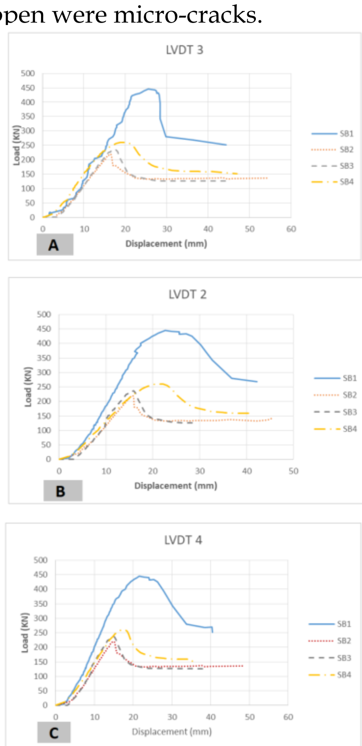


Fig. 6 Failure mode for specimens
(A) SB1 Tension side (B) SB2 Compression side
(C) SB2 Tension side (D) SB3 Tension side
(E) SB4 Tension side

Fig. 6 illustrated the crack's patterns for experimental study. Narrow diagonal cracks appeared and propagated from the column face to the supported edges of the slab perpendicular to the free edge. The direction of cracking tended to be in two directions; this led to the hypothesis that the fibers were randomly oriented as expected. The specimen took a long time deforming before breaking so it means ductile failure that is uncanny for punching shear failure. The failure of the slab occurred when the cone of failure radiating outward from the point of load application pushed up through the slab body. There was a horizontal narrow crack between the column and the top slab surface at the compression side as shown in **Fig. 6**(B). The presence of micro steel fibers in the specimens prevented an explosion during loading and all the cracks that happen were micro-cracks.



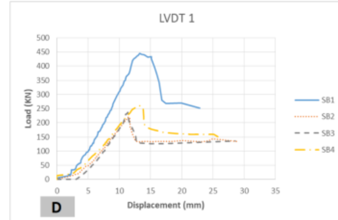


Fig. 7 Load vs. displacement comparison
(A) Point 3 (B) Point 2
(C) Point 4 (D) Point 1

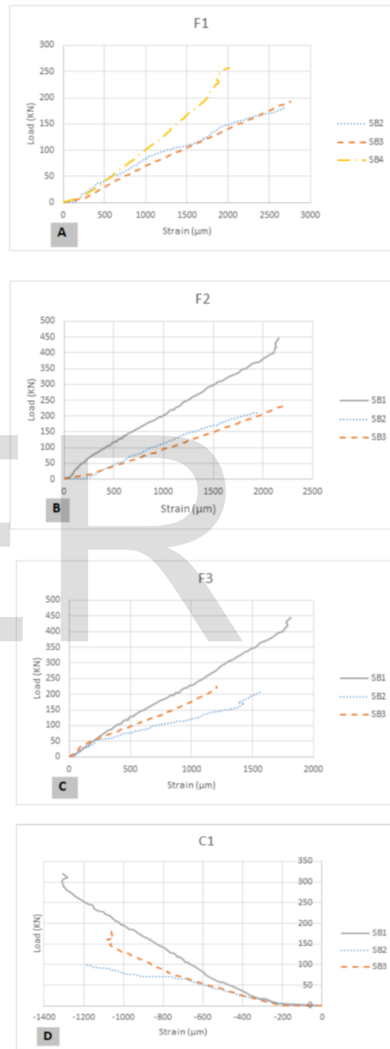


Fig. 8 Load vs. strain comparison
(A) Location 1 (B) Location 2
(C) Location 3 (D) Concrete location 1

The strains that were not referenced in chars have malfunctioned during casting. Some strains give recorded unrealistic values and the others give zero reading. As elucidated in charts, F1 recorded the highest value compering to all strains. The strain decrease when going away from the column face as saw F1, F2, and F3 as demonstrated in Fig. 8.

The flexure reinforcement bar of specimen SB1 did not exhibit higher strains as expected. Because the concrete

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strength in specimen SB1 was very high so it prevents more yielding in the flexure reinforcement bar and carried the tension force that produced.

The concrete strain C1 recorded negative reading because it measuring the compression strain of the concrete. The strain at C1 recorded reading analogous to the concrete strength of each specimen. This means when concrete strength increase in specimen the compression strain increase but the flexure reinforcement bar strain decrease.

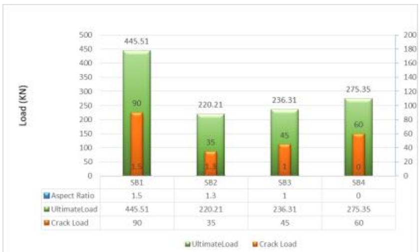

Fig. 9 Column aspect ratio compared to the ultimate load and crack load.

Fig. 9 highlights the ultimate load and crack load relation with the column aspect ratio. As shown the SB1 had the largest value of ultimate load and crack load, not only for column effect (100*150)mm with aspect ratio 1.5 but also had the highest concrete strength compared with other specimens so SB1 was out of comparison. After SB1 was SB4 with a circular column dimension 150mm diameter. The aspect ratio for specimens SB2 and SB3 was 1.3 and 1 respectively, with column dimension (100*130)mm and (120*120). As presented, SB4 recorded ultimate load and crack load higher than SB3 which means the specimen with a circular column carries the higher than specimen SB3 with a square column dimension. Finally, specimen SB2 had recorded the lowest ultimate load, and crack load which had a rectangle column dimension.

5 Conclusions

- UHPC showed crucially enhanced material properties relative to traditional concrete and HPC.
- Using micro steel fibers in UHPC increasing compressive strength three-time comparing with UHPC without micro steel fibers, which means the key to making UHPC by adding micro straight circular steel fibers to your mixture with 2% of concrete volume.
- Decline the amount of water as conceivable with saving workability at a fresh state producing high compressive strength concrete.
- Pan mixer instrument must use in preparing UHPC, It makes amazing phenomena without extra water or superplasticizer adding as you calculated only leave compound mixing and become inflow and fulfill very homogenous.
- UHPC is a very sensitive material and any change or disturbance in partial quantity or mixing procedures leads to a collapse in the concrete results.
- The presence of micro steel fiber in the UHPC prevented specimens from an explosion during loading and all the cracks that happen were micro-cracks.
- As expected for UHPC, the presence of micro steel fiber in the specimens changed the average value between a load value at appearance cracks and ultimate load by about 81% difference. Also, a huge difference at point "d/2" from column face in the average value between cracks deflection, ultimate deflection, and fracture deflection. The difference between the deflection average value at appearance cracks and ultimate deflection average value about 67.5% and the difference between ultimate deflection average value and fracture deflection average value about 58% while the difference between the deflection average value at appearance cracks and fracture deflection average value about 86.75%.Not only, the load-defection of SB1 difference from other specimens by 22.7%, while for load-deflection of SB4 by a difference 11.4%. SB2 had the largest fracture deflection point value than other specimens a difference of 19.3%.
- The average difference between ACI analytical results and the laboratory experimental result the maximum capacity load of four specimens was 26.07%, which confirms the known the codes and guides book is more conservative and tory.

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