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Flexural Strength of Steel Fiber Ultra High Strength Concrete Beams under Static and Repeated Loads

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A B S T R A C T

The goal of the present work is to study the performance of Ultra High Strength Concrete (UHSC) beams in flexure under static and repeated loads. The main considered variables are the main reinforcement ratios which are (0.0129, 0.0204, and 0.0323), and the method of applying load. For each reinforcement ratio two beams were casted, one of them was tested under four points static load and the other one under repeated load up to failure. The behavioral characteristics of Ultra High Strength Concrete dominantly depends upon its load history, for this purpose experimental investigation of the behavior of (UHSC) beams under load history of repeated cycles is performed as well as that it is compared with the behavior under static load. The average cube compressive strength of the UHSC used in casting the beams was as high as (124 N/mm2). The load deflection curves, first cracks and failure loads, crack pattern, and concrete strain distribution over the depth of the beams were presented.

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مقاومةالانثناء للعتبات الخرسانية فائقة الاداء والمسلحة بالألياف الفولاذية تحت تأثير أحمال ساكنة ومتكررة

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الخلاصة

الهدف من هذا البحث هو دراسة تصرف العتبات الخرسانية فائقة المقاومة للانثناء تحت تأثير احمال ساكنة وتكرارية. المتغيرات الرئيسية التي تم تضمينها في البحث هي نسبة التسليح الرئيسية والتي كانت كالاتي (0.0204, 0.0129, 0.0323), وطريقة تسليط الاحمال. لكل نسبة تسليح تم صب عتبتين احداهما تم فحصها تحت تأثير احمال ساكنة والاخرى تحت تأثير احمال تكرارية حتى الفشل. الخواص السلوكية للخرسانة فائقة المقاومة غالبا تعتمد على تاريخ التحميل، لهذا السبب تم اجراء دراسة عملية على تصرف العتبات الخرسانية فائقة المقاومة تحت تأثير دورات تحميل متكررة وكذلك تمت مقارنتها

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مع التصرف تحت تأثير احمال ساكنة، معدل مقاومة الانضغاط للخرسانة فائقة المقاومة المستخدمة لصب العتبات وصلت الى(124 N/mm^2) . منحنيات الحمل -الاود، حمل التشقق الاول، حمل الفشل، شكل التشققات وكذلك انفعال الخرسانة وتوزيع الانفعال على عمق العتبة تم اجراءها من اجل دراسة تصرف الخرسانة فائقة المقاومة تحت تأثير الانثناء.

1. INTRODUCTION

Ultra-high strength concrete (UHSC) reinforced with steel fiber was advanced during latest years [1,2]. UHSC shows superior compressive and tensile mechanical behavior, in addition to its remarkable durability properties. UHSC also known as reactive powder concrete (RPC) [3] which can be defined as a high strength ductile material made by mixing Portland cement, fine sand, silica fume, quartz powder, high range water reducer, water and steel fibers. The nonappearance of coarse aggregate was considered by originators to be a reason for the microstructure and the performance of the UHSC to reduce heterogeneity between cement matrix and the aggregate. However, as a result of using very fine sand as an alternative of ordinary aggregate, the cement content in UHSC is as high as (900-1000 Kg/m^3) [4]. The flexural strength is a very essential property to determine the rupturing capacity. On the other hand, the flexural strength alone is not enough to recognize the whole fracture mechanism. After beginning of crack a tensile softening behavior in concrete occurred due to the fiber that bridge the crack [5]. Ref. [6] studied the essential behavior of ultra-high-performance concrete (UHPC) beams reinforced with steel fibers. The study involved the main reinforcement ratio which was less than 0.02 and the method of employing the ultra-high-performance concrete. The bending actions of UHPC members were considered by multi micro cracking and a localized macro crack. Reactive powder concrete showed high performance under flexural loading. Well toughness and reinforcing effect of the steel fibers were exhibited as a result of high post peak load carrying capacity. Unexpected load decrements and increments were detected in the downward branch. This behavior is properly related to the content of fiber, gradual pulling out of the fiber and fiber bond [7]. Wasan, and Tayfur [8] studied the flexural behavior of eleven (150x150x1950 mm) ultra- high performance concrete beams containing steel fiber with volume fraction (0.5, 0.75 and 1 %). The experimental results displayed that the addition of steel fiber slightly enhanced the load deflection relationship and ultimate load for beams samples. Sung et. al. [9] studied the range of maximum tensile steel ratio which has practical ductility measurements and flexural performances of UHSC through the flexural test. The reinforced UHSC beams exposed to flexural moment show more brittleness thanthe reinforced restrained strength concrete beams having similar reinforcement ratio (ρ/ρb). Ten specimens with single reinforced rectangular section beams with 150MPa concrete compressive strength are experienced to assess their flexural performance. It has been concluded that the minimum ductility ratio with above (3.0) for double actuator. The compressive strength for the tested beam was 216 MPa and the splitting test result was 9.8 MPa. reinforcement beam and above (2.0) for single reinforcement beam, limit strain should be fixed so that the net tensile strain of outermost tensile steel may be above (0.006) in excess of 0.005 and the steel ratio in tension face of the section is essential to be (0.55 ρb) or less.

Graybeal et. al. [10] investigated the flexural behavior of an ultra-high-performance concrete (I-girders), a full scale pre-stressed I-girder with (193MPa) compressive strength steel fiber reinforced concrete was tested and analyzed. A span of 24.4m long ASSTTO Type II girder encompassing 26 pre-stressing strands and a mild steel reinforcement was fabricated. It had been concluded that the UHPC girders displayed flexural capacity greater than those of traditional concrete girders with similar cross-sectional geometry. The flexural design of UHPC I-girders could be accomplished in a normal manner through the use of a conventional approximation of the behavior of concrete stress-strain.

Aravind et. al. [11] made an investigation on high strength reactive powder concrete using available materials specifically silica fume, silica powder and ordinary Portland cement. The curing cycles are employed only under normal water curing. The maximum cube compressive strength obtained in 28 day is 87 N/mm^2 using steel fibers. Further, split tensile test and flexure testing is also conducted. The reactive powder concrete is then used in flexure beam, the ultimate load obtained was 90kN followed by maximum deflection is 9.3mm and stiffness is 8.7 kN/mm which is effective for the structural purposes.

Bae et. al. [12] made a study to evaluate the flexural strength models for ultra- high strength steel fibers concrete beams using rectangular, triangular stress block, and real distribution shape in compression face. Slender beam specimen of 200mm by 350mm cross section with span of 4.3 m was used to perform a test by four-point loading with 2000 kN actuator. The compressive strength for the tested beam was 216 MPa and the splitting test result was 9.8 MPa. Twenty –one test results from previous published papers were used to evaluate the proposed models for flexural strength. It was concluded that the most accurate model for ultra-high-performance concrete under compression is triangular one. This paper presents an experimental investigation to determine the flexural behavior of UHSC beams. Six beams designed to fail in flexure, three of them tested under monotonic load and the other three under repeated load in order to examine the effects of repeated strength degradation of UHSC concrete matrix.

2. EXPERIMENTAL PROGRAM

2.1 Materials

1. Cement: The cement used in producing UHSC was sulfate resisting Portland cement manufactured locally named (Al Mass cement) of grade 42.5 MPa. The physical properties of this type of cement are shown in Table 1 and it confirms to the British Standards, B.S. 12/1971 [13] .
2.
3. Fine aggregate: The fine aggregate used in this study was the local river sand, which was washed, dried and sieved. For UHSC, very fine sand with maximum size of 600μm is normally used. The grading satisfied the fine grading according to B.S. specification No. 882/1992 [14].
4. Steel fibers: The HAREX steel fiber was used in this study which had a flatten cross section. The length of the fiber is 16 mm, with aspect ratio of 21.8.
5. Chemical admixture: A high performance concrete super plasticizer, which is based on polycarpoxylic technology, PC- 200 hyperplast was used in the present study.
6. Mineral admixtures: A white undensified silica fume (SF) with Blaine finesse of about 20m^2/g was used.
7. Quartz powder: with particle size less than (0.25 mm)
8. Steel: Mild steel bars of diameters (10, 16, 20, 25) mm were used. Tension test was conducted to find out the properties of steel bars, the details are given in Table 2.

2.2 Mix Proportion

Table (3) shows the mix proportions used in the present work.

Table 1
Physical Properties of Cement

Property	Measured	B.S Standards [12]
Initial setting time (min)	114	≥ 45
Final setting time (hrs.)	6	≤ 10
Compressive Strength (3 days)	22	≥ 15
Compressive Strength (7 days)	31	≥ 23

Table 2
Steel properties

Bar Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation %
10	596	695	11
16	522	653	14
20	530	670	16
25	580	703	18

Table 3
Ultra High Strength Concrete Mix Proportion

Ingredient	Quantity
Cement	712 Kg/m^3
Fine Sand	1020 Kg/m^3
Silica Fume	231 Kg/m^3
Quartz Powder	211 Kg/m^3
Steel fiber	160 Kg/m^3
Superplastizer	2 liter/100 kg Cement
W/C Ratio	0.24
W/B (cement+silica)	0.18

2.3Beam Samples:

Six ultra-high Strength concrete beams with cross section of (150mmx250mm) simply supported on (2.35 m) span. Three main reinforcement ratios (0.0323, 0.0204, and 0.0129) were used, for each reinforcement ratio two beams were casted one of them was tested under static load and the other under repeated load. Each beam was reinforced with φ10mm bar diameter stirrups as shear reinforcement spaced at 100mm c/c. The test setup, the details of the beam specimens and reinforcement is displayed in Fig.1.

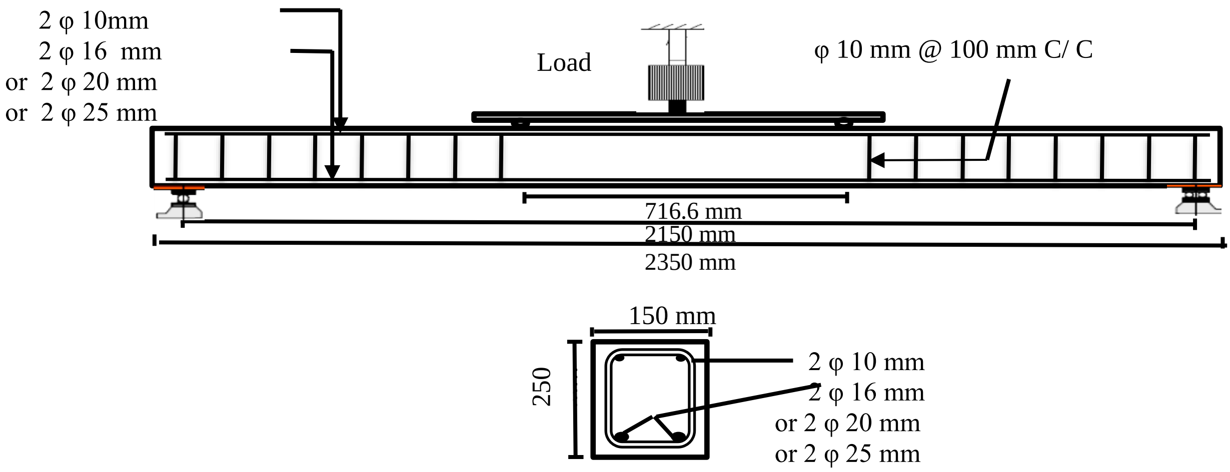
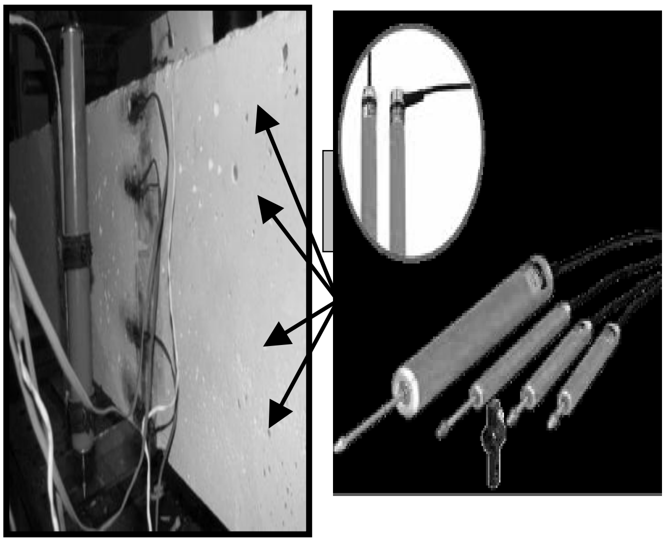


Fig.1. Beam Cross Section and Reinforcement Details.

Fig. 2 displays the location of the strain gages that were fixed at the beam side and the displacement transducer (SDP-300D); where these strain gages are fixed at mid span of the beam to measure the strain distribution along the beam depth. The displacement transducer was installed at the mid span of the beam to measure the deflection by connecting it to the data logger system (TD3-303) and then to windows PS with software TC-7100 as shown in Fig. 3.



(a) (b)

Fig. 2 (a) Location of the Strain Gages for the Beams and (b) Transducer Details.

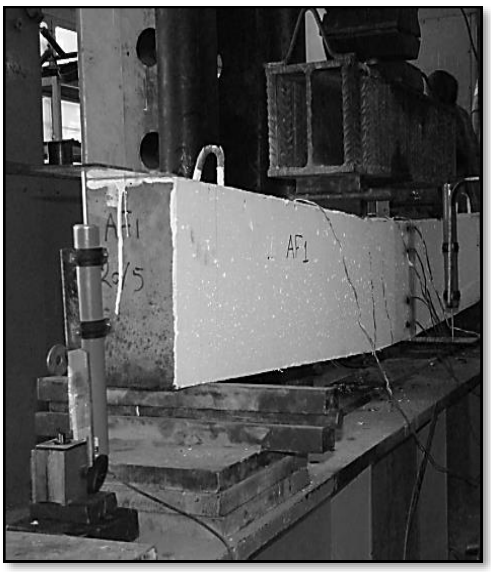


Fig.3 Location of the Transducers to Measure the Beam Mid Span Deflection and End Rotation.

3. RESULT AND DISCUSSION

3.1 Behavior of Beams Under Static Load

The load-mid span deflection curves are presented in Figures (4). The load deflection curve for beam (B-A-M and B-B-M) was more ductile than that for beam (B-C-M).The reason for the inductile behavior is due to its relatively high main reinforcement ratio relative to the other two beams. For those three beams load-deflection curves are linear with a sharp slope up to (80%, 87%, and 100%) of the experimental failure load; within this load first cracking occurs. The graph changes its nature after first cracking i.e. its slope changed this is referred to the change in crack depth with the load increment. This crack is observed from concrete cracks pattern and crushing plots. Tension failure of UHSC beams usually happens when the steel fiber initiates to pull out of the matrix. At that location the crack width became considerably wider than any other crack in the beam, as presented in Figure (5). Finally, the fibers connecting the highly stressed crack initiated to pull out. Subsequently, the beam fails when local bond failure between fibers and the UHSC matrix take place, this case is noted in beams (B-A-M and B-B-M). Table 4 summarizes the experimental results obtained from this study.

Table 4
Experimental Results of the Tested Beams.

No.	Beam	Compressive Cube Strength f_{cu} (N/mm2)	Splitting Tensile Strength (MPa)	First Cracking Load (kN)	Ultimate Load (kN)
1	B-A-M*	116	6.8	32	144.0
2	B-A-R**	118	7.0	35.5	147.0
3	B-B-M	123	6.7	31	200.0
4	B-B-R	122	6.5	33.7	212.0
5	B-C-M	136	7.5	40	307.0
6	B-C-R	131	7.0	37.5	320.5

* M -Monotonic Load

**R- Repeated Load

A-main reinforcement ratio=0.0129

B- main reinforcement ratio=0.0204

C- main reinforcement ratio=0.0323

For beam (B-C-M) a linear elastic behavior is found as the load increased to its maximum value, after that the load suddenly decrease due to crushing in the compression top face and brittle fracture taken place. This is due to high reinforcement ratio as compared with the other two beams.

Strains in concrete corresponding to each stage of loading were measured in both compression and tension zone, flexural strains were clear only up to about 50% of the ultimate load due to cracking. For this reason, the strains at final stages of loading were not taken into consideration. In general, the strain distribution is taken at a load of about (10%) of the total failure load for each beam in the elastic stages of loading.

Strain distribution along the beam depth is presented in Figure (6) for the three beams. the strain distribution at a load less than the cracking load, thus the neutral axis depth is about h/2 because the forces carried by the steel reinforcement before cracking is very small and it can be neglected. The compressive concrete area that corresponds to the stress of tensile area decreases significantly with decreasing the main reinforcement ratio where the strain at the bottom strain gage for beam (B-A-M) is greater than the steel strain in beam (B-B-M).

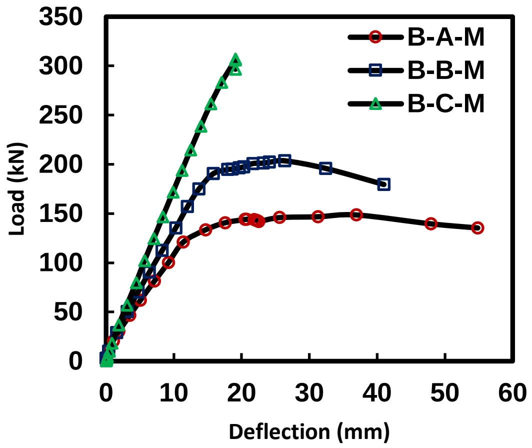


Fig. 4. Load Deflection Relationship for Beams (B-A-M, B-B-M, and B-C-M) under Static Loads.

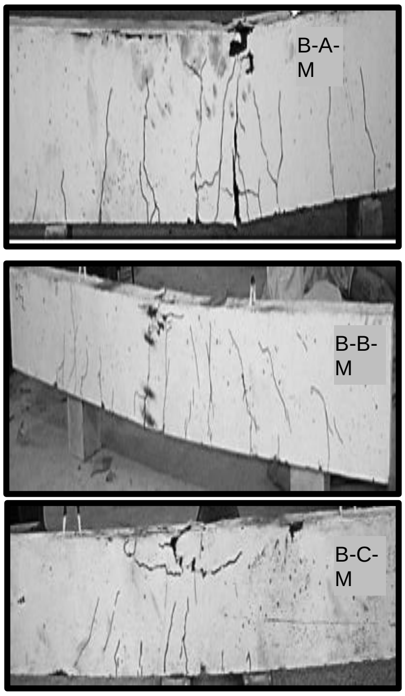


Fig. 5. Crack Pattern for Beams (B-A-M, B-B-M, and B-C-M) under Static Load Test.

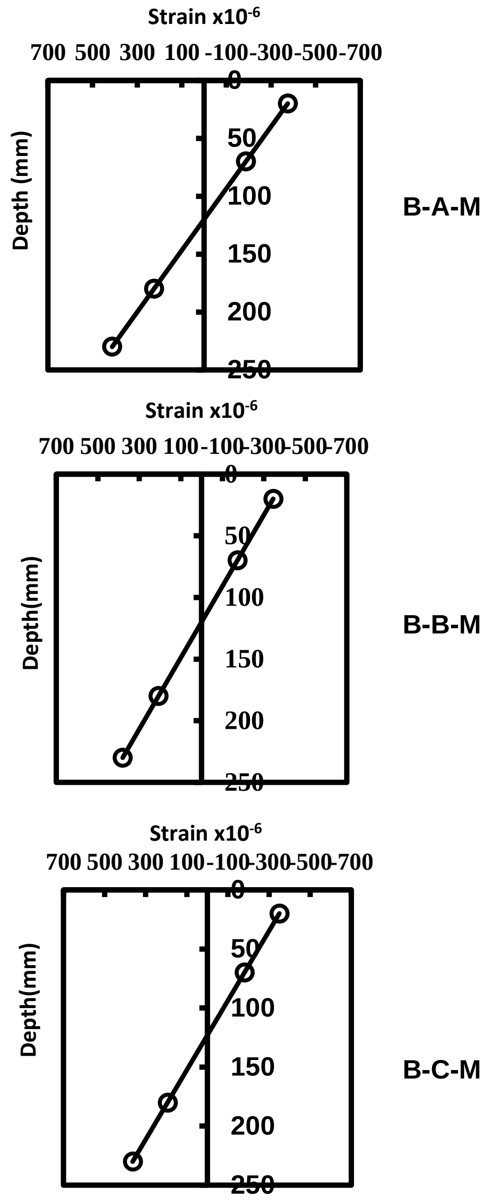


Fig. 6. Concrete Strain Distribution along the Beam Depth at Load of 29kN.

3.2 Behavior of Beams Under Repeated Load

The process of testing the beams under repeated loads is performed by applying the load from zero to a certain value and then release the load to a value near zero, and then applying the next step of load to a certain value and re-loading again and so on until the occurrence of failure. The number of cycles was selected to be 5 cycles. The load deflection curves for the three tested beams (B-A-R, B-B-R, and B-C-R) with three different main reinforcement ratios (0.0129, 0.0204, and 0.0323 are shown in Figs. 7, 8, and 9 respectively. For beam (B-A-R) five cycles are applied with load increase of 25 kN for each cycle and the failure occurs at load (147kN) at the fifth cycle, beam (B-B-R) also loaded with five cycles with (50kN) increase every cycle and the failure load was (212kN).

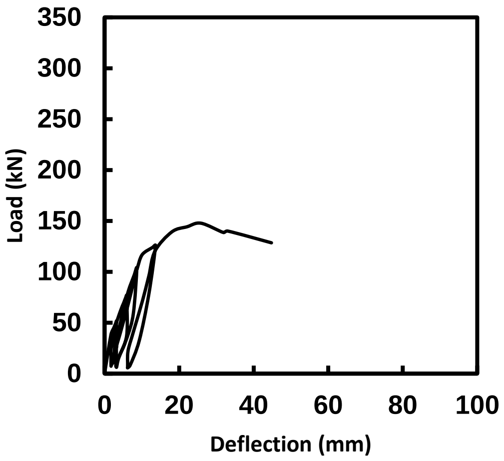


Fig.7. Load Deflection Curve for Beam B-A-R under Repeated Load.

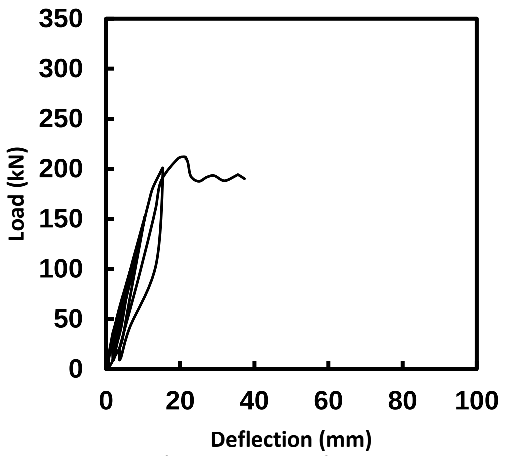


Fig. 8. Load Deflection Curve forBeam B-B-R under Repeated Load.

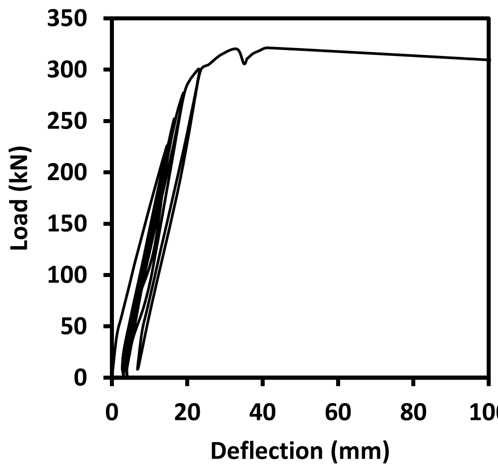


Fig. 9. Load Deflection Curve for Beam B-C-R under Repeated Load.

Finally beam (B-C-R) failed after five cycles the first one increased from zero up to (225kN), and the remaining four cycles load increment are increased by (25kN). The detected load - deflection relation of the tested beams is linear before cracking of the concrete. After cracking, slope of the curves (secant stiffness) reduces with the increase of deflection and the loops of the beams containing less main reinforcement ratio were wider than those for beams with greater reinforcement ratio and showing larger area enclosed by the curves. The energy dissipation in the first cycle of each displacement level was greater than those in the subsequent cycles because of the development, widening or propagation of crack occurred in first cycle. The variation in the energy dissipation in first and repeated cycles was severe in case of beam containing higher main reinforcement ratio i.e. (B-C-R). The possible explanation of greater value of dissipated energy in first cycle of loading is that when deflection is increased, crack is extended and the fibers present in the path of the crack resist their propagation causing much energy dissipation. Due to the high stress level, the fibers break or pull out in first cycle and little damage of fibers occur in subsequent cycles of loading at the same deflection value. The crack pattern of the beams is presented in Fig.10. Beam B-C-R fails by crushing of concrete at mid span after the initiation of flexural cracks which were spread in tension face along the span of the beam. Beams (B-A-R) and (B-B-R) failed in tension, the crack width became significantly wide. Finally, the fibers bridging the stressed crack initiated to pull out.

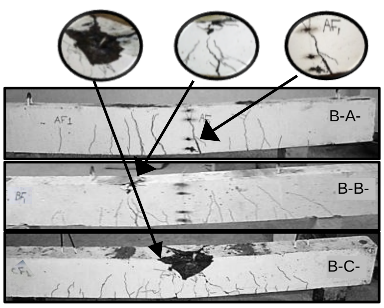


Fig. 10. Crack patterns of the tested beams B-A-R, B-B-R, and (B-C-R).

4. CONCLUSIONS

1. The bending performance of UHSC members was noticed by multi-micro cracking and a local macro crack.

2. A linear elastic behavior is found as the load increases to its maximum value, after that the load is usually decreases due to secondary compression crushing at top face of the beam.

3. The interaction of the fiber reinforcement with the UHSC matrix permits small width, closely spaced cracks to occur and allows the UHSC to carry tensile loads after cracking; It is perceived that when steel fibers are used, the shear crack propagation becomes slower and more gradual and shows a significant post-cracking load capacity before the complete failure of the UHSC beams was achieved.

4. The load deflection relationships obtained under statically increasing load are similar to the envelopes of hysteretic behavior obtained under repeated cyclic reinforcement ratio were wider than those beams with greater reinforcement ratio and showing larger area enclosed by the curves
5. The energy dissipation in the first cycle of loading was greater than those in the subsequent cycles.
6. would provide sufficient strength envelope for hysteretic behavior of the beams and it was observed that the loops of the beams containing less main

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