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FLEXURAL BEHAVIOR OF BASALT FRPRC BEAMS UNDER REPEATED LOAD

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ABSTRACT

Recently fiber-reinforced polymer (FRP) has become a practical alternative construction material for replacing steel bars as reinforcement in concrete structures to overcome the corrosion related problems. The recently developed basalt fiber-reinforced polymer (BFRP) is a valid alternative to carbon fibers for their lower cost and to glass fibers for their strength. However, the performance of Basalt reinforced concrete elements subjected to repeated loading, which is a critical design limit for bridge beams, has not been fully explored. Also the brittleness and low modulus of elasticity of BFRP greatly reduces the stiffness of BFRP-reinforced concrete (BFRPRC) beams. The aim of this experimental study is to investigate the flexural behavior of concrete beams reinforced with Basalt fiber reinforced polymer (BFRP) bars when they subjected to repeated loadings and to improve their stiffness. For this purpose an experimental program was set up on eight specimens consisting of pure Basalt FRPRC beams and hybrid BFRPRC beams with 2050 mm length and a cross-section of 150 x 200mm were carried out and tested under static or repeated loading followed by static loading up to failure. The results were discussed and analyzed. The test results indicated the contribution of adding steel reinforcement to concrete beams reinforced with BFRP bars. Finally some valuable conclusions and recommendations were given.

Keywords: repeated loading, FRP, BFRP, hybrid, RC, FRPRC

2. Introduction

Many reinforced concrete structures in severe environment are susceptible to steel corrosion and structural decay resulting in costly repair and service inconvenience. In order to avoid such problems, the use of fiber-reinforced polymer (FRP) bars as internal longitudinal flexural reinforcement has emerged as an alternative solution. In addition to their noncorrosive nature, FRP bars have a high strength-to-weight ratio making them attractive as reinforcement for concrete structures. [1, 2, 10]. FRP reinforced concrete members behave differently from these reinforced with traditional steel. FRP bars have

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higher strength, but lower modulus of elasticity than steel, and exhibit linear stress–strain response up to failure. The lower modulus of elasticity of FRP causes a substantial decrease in the stiffness of FRP reinforced concrete beams after cracking and consequently higher levels of deflections under service conditions. [1,3,10].

To date, many experimental tests have been conducted to investigate the flexural behavior of FRP-reinforced concrete beams [1–9], and the flexural capacities of concrete beams reinforced with FRP bars and comparisons of the structural performance of these beams with that of conventional steel-reinforced concrete beams have been well documented. Bond–slip has a significant effect on the structural behavior of FRP-reinforced concrete structures due to the weaker bond characteristics between FRP rebars and concrete comparing with the conventional steel rebars [14].

In the last two decades, the use of high-strength materials has resulted in lighter concrete structures with a decreased dead load. This decrease in dead load combined with an increase in live loads (heavier trucks on bridges for example) has resulted in an increased live to dead load ratio [11,15]. Therefore, the effect of the loading–unloading (repeated loading) of live loads on structures such as bridges and marine structures is now more pronounced than before [11]. Repeated loading causes an accumulation of damage under service loads that are far below the ultimate loads. This damage takes the form of an increase in the number of cracks, the crack widths and the deflection [16,17]. In extreme cases, repeated loading can cause a structure to fail by fatigue [11]. In addition, repeated loading may cause cracks along the longitudinal bar to develop, thus decreasing the bond strength and increasing the slip between bars and concrete [12,13]. Relatively very little work addressing the flexural behavior of concrete beams reinforced with Basalt fiber reinforced polymer (BFRP) rebars under repeated loading.

El-Ragby et al. (2007) [18] tested six full-size bridge deck prototypes of length 3000 mm, 2500 mm width and 200 mm thick which were reinforced with five GFRP bars and one conventional steel bar using different reinforcement ratio under both constant fatigue loading and accelerated fatigue loading with variable amplitude and concluded that GFRP reinforced slabs had the lowest residual deflection, greatest stiffness and a longer fatigue life about three times than the steel reinforced slabs.

Kae-Hwan and Jong-Gun, (2001) [19] studied the damage mechanism due to shear fatigue behavior of FRP reinforced concrete slabs under repeated loading. The relationship between number of cycles and deflection, crack growth and modes of failure with the increase of number of cycles, fatigue strength and S-N curve were observed. The bond strength of GFRP bars under fatigue was studied by Adimi et al, [20].

Experimental tests were carried out on forty concrete slabs of size 2.4 x 0.6 m by Sivagamasundari and Kumaran [21] to investigate the flexural behavior of concrete one way slabs reinforced with Glass Fiber Reinforced Polymer (GFRP) reinforcements as well as conventional (steel) reinforcements when subjected to static and repeated loadings. Twelve slabs were reinforced with steel and the remaining slabs with GFRP bars. Twenty slabs were tested under static loading condition and another twenty were tested under repeated loading condition. They [21] observed that, the fatigue response of sand coated GFRP reinforced slabs is superior to all the other types of slabs.

In this paper, experimental tests were carried out to investigate the flexural behavior of FRPRC members by means of their load-displacement relationships, pattern of cracks, mode of failure, cracking and ultimate load. Eight FRPRC members, either pure or hybrid RC members were fabricated and tested under static and repeated loading. The type of FRP used in all the FRPRC members was Basalt fiber reinforced polymer (BFRP). The variables investigated were (P_r/P_u) ratio and $A_f /(A_f +A_s)$ ratio in hybrid reinforcement with the constant A_s. Where A_f , A_s = area of BFRP and steel bars respectively.

3. Experimental program

3.1. Materials

All beams were made using high strength concrete having concrete compressive strength of about 50 N/mm^2, which is evaluated by six cubic specimens with the side length of 150 mm. Table (1) shows the mixing proportions of the concrete material. The used concrete was made from Ordinary Portland Cement, local sand and aggregate of 10 and 20 mm maximum nominal size in addition to Silica Fume and admixture. The used sand has specific weight, bulk density and fineness modulus of 0.025, 17 kN/m^3 and 2.43 respectively. The water cement ratio w/c was 0.32 for all batches. The yield tensile strength of the steel rebars, as determined by standard tensile test was 438 N/mm^2. The tensile strength and elastic modulus for BFRP bars are about 1150 MPa and 55 GPa respectively, as given by the manufacturer.

Table 1.
Mixing properties of concrete materials.

Cement kN/m^3	Sand kN/m^3	Aggregate (A) <10mm kN/m^3	Aggregate (B) <20mm kN/m^3	Silica Fume kN/m^3	Addicrete (BVF) Liter/m^3	Water Liter/m^3
4.5	4.7	4.7	4.7	0.7	15	144

3.2. Details of the tested beams

Eight rectangular concrete beams were constructed and tested in this work. Three of them were tested statically and five under repeated loading. The beam specimens containing either basalt fiber reinforced polymer (BFRP) bars or a combination of both Basalt FRP and steel rebars were investigated. The beams were 2050 mm long, with rectangular cross section of 150 x 200 mm, as shown in Fig. (1). Basalt FRP rebars of 8 mm in diameter and steel bars of 10 mm in diameter were used as the longitudinal main bars. Two steel rebars of 8 mm in diameter are used as compression reinforcement for these beams. Steel stirrups of 8 mm in diameter and 125 mm spacing are used as shear reinforcement. Table (2) as well as Fig. (1) Show the details of the main parameters considered in this investigation.

3.3. Preparation of test specimens and Test procedure

The concrete was batched in the laboratory using a pan mixer, placed by hand in wood forms and compacted using a 25 mm diameter electric vibrator. Control specimens including cubes of 150 cm side length were cast from each batch. The tested beams and the corresponding control specimens were tested in the same day after 28 days from casting. All the beams were simply supported over a span of 1600 mm and the load was applied to the

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beams through two points as shown in Fig. (1). In static tests, the loading was applied in increments of 5 kN. In repeated tests, the fatigue loading was applied as stationary pulsating two concentrated load at the mid-span of the beam. The applied minimum load was constant at 14 kN (weight of testing machine steel tar). The maximum load was 0.5, 0.65 and 0.75 of the ultimate virgin static load, see Table (2). The frequency of loading was 500 cycles per minute. The stroke of piston was adjusted at value of 0.1 mm. The loading regime is shown in Fig. (2). Mid-span deflection at each increments, first cracking load and failure load were measured. The crack patterns and failure modes were observed carefully.

Table 2.
Details of tested beams

Beam No.	Cross sec. (b*t) (mm)	f_{cu} N/mm^2	Comp. steel	A_f	A_s	Pr/Pu (%)	Type of loading
A1	150*200	48.3	2Φ8	6Φ8	-	-	static
A2	150*200	49.1	2Φ8	4Φ8	2Φ10	-	static
A3	150*200	50.2	2Φ8	2Φ8	2Φ10	-	static
A4	150*200	49.1	2Φ8	4Φ8	2Φ10	50	repeated
A5	150*200	49.1	2Φ8	4Φ8	2Φ10	75	repeated
A6	150*200	49.1	2Φ8	4Φ8	2Φ10	65	repeated
A7	150*200	48.3	2Φ8	6Φ8	-	65	repeated
A8	150*200	50.2	2Φ8	2Φ8	2Φ10	65	repeated

Where: P_r = Repeating load, P_u = Ultimate load.

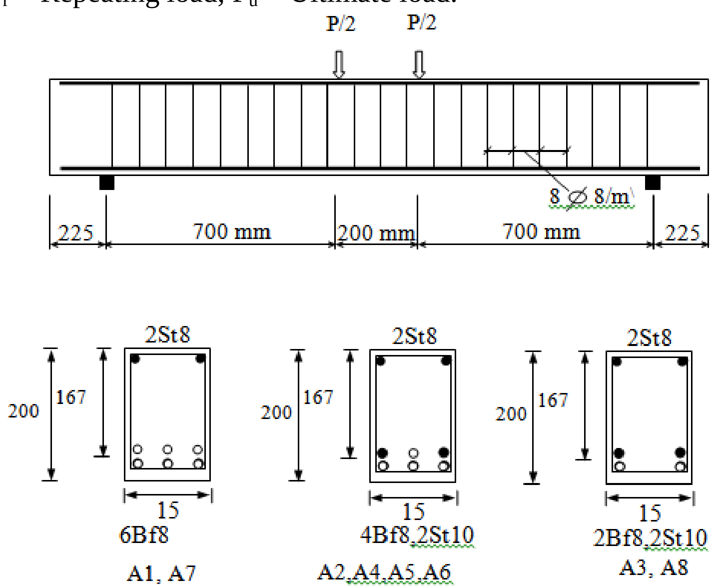

Fig. 1. Details of the tested beams and test setup.

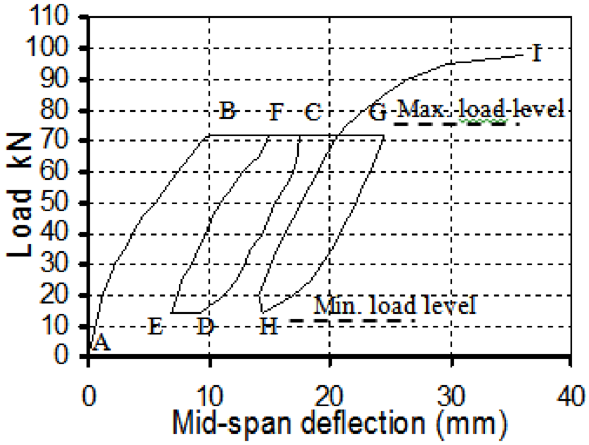

Fig. 2. Sketch of repeated loading sequence versus deflection.

Where: AB – First static cycle, BC – Repeated loading (500,000 cycle).
ED – Rest period (eight hour), FG – Repeated loading (500,000 cycle).
HI – Final static cycle.

4. Test results and discussion

4.1. Load deflection diagrams

Table (3) shows the value of the recorded mid-span deflection for the tested beams corresponding to cracking and ultimate loads. The maximum deflection (Δmax) shown in this table was taken as the value corresponding to 90% of the ultimate load. The load mid-span deflection relationships of concrete beams A4, A5, A6, A7 and A8 testing under repeated loading are given in figures 3, 4, 5, 6 and 7 respectively. These figures shows the progressive variation of the load deflection hysteric's loop between two load level P_{min} and P_{max}, with increasing the load cycles. Also through these figures it can be seen that, the total increase in deflections due to repeated loading increased as the number of cycles increased. The great portion of this increase occurs in the latest stages of repeated loading of about 600000 cycles for beam A7 reinforced with BFRP bars only. For hybrid beams (reinforced with Basalt FRP and steel bars), the deflection increment have been controlled by presence of steel bars.

The load deflection performance of beams loaded to failure after one million cycles in comparison with their identical static beams are shown in figures 8, 9 and 10 for beams A7, A8 and all of A4, A5, A6 respectively. It is clear from these figures that due to repeated loading history of one million cycles at the final static test, an improvement in the stiffness of the tested beams leading to more steep load deflection curves, specially in hybrid beams (reinforced with Basalt FRP and steel bars). The total deflections prior to failure for the tested hybrid beams under repeated loads are nearly similar to that of the comparison identical beam tested statically. However, the total deflections prior to failure for BFRP beam reinforced with BFRP bars only under repeated load was more than that of the identical beam under static load.

Figure (11) shows that, mid-span deflection at any load level after one million cycles for beam A6 having $A_f /(A_f + A_s)$ ratio equal 0.56 is smaller than that beams A7 and A8 having $A_f /(A_f + A_s)$ ratio equal 1 and 0.39 respectively.

Figure (12) represented a plot for the measured maximum deflection against the number of applied load cycles for various beams tested under repeated loading. It is obvious from this figure that, the deflection increases regularly as the number of cycles increases for hybrid beams. However for Basalt FRP concrete beams, the deflection was increased rabidly between 400000 and 600000 cycles. This result confirms that presence of steel bars in BFRP concrete beams controlled the deflection under repeated and static loading. The total deflection after one million for beam under maximum repeated load 0.75 of the ultimate virgin static loads is more than that for beams under maximum repeated load 0.5 and 0.65 of static loads.

Table 3.
Cracking and ultimate deflection for tested beams

Data of tested beams						**Deflections**		**Type of loading**
Beam No.	**f_{cu} N/mm^2**	**A_f**	**A_s**	A_f / (A_f + A_s)	(P_r/P_u) %	**Δ_{cr} (mm)**	**Δ_{max} (mm)**	
A1	48.3	6Φ8	-	1	-	2.9	37	Static
A2	49.1	4Φ8	2Φ10	0.56	-	1.5	34	Static
A3	50.2	2Φ8	2Φ10	0.39	-	1.3	27.5	Static
A4	49.1	4Φ8	2Φ10	0.56	50	1.5	28	Repeated
A5	49.1	4Φ8	2Φ10	0.56	75	1.5	41	Repeated
A6	49.1	4Φ8	2Φ10	0.56	65	1.5	26.5	Repeated
A7	48.3	6Φ8	-	1	65	2.9	55	Repeated
A8	50.2	2Φ8	2Φ10	0.39	65	1.3	25	Repeated

Where: P_r = Repeated load, P_u = Ultimate load.

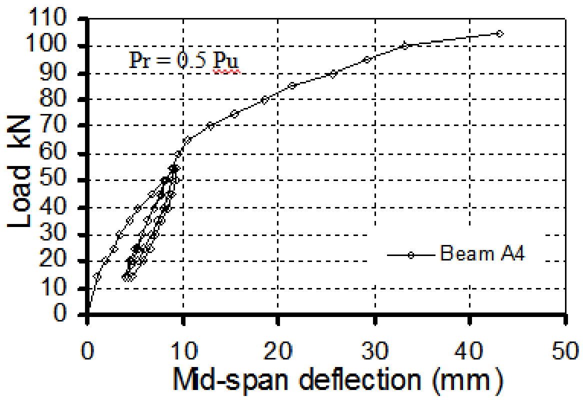

Fig. 3. Load mid-span deflection curve for beam A4 under repeated load.

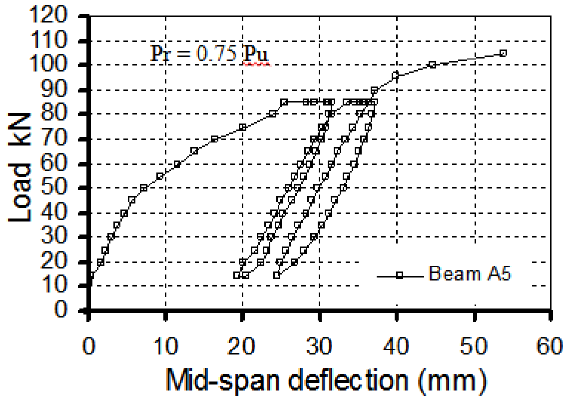

Fig. 4. Load mid-span deflection curve for beam A5 under repeated load.

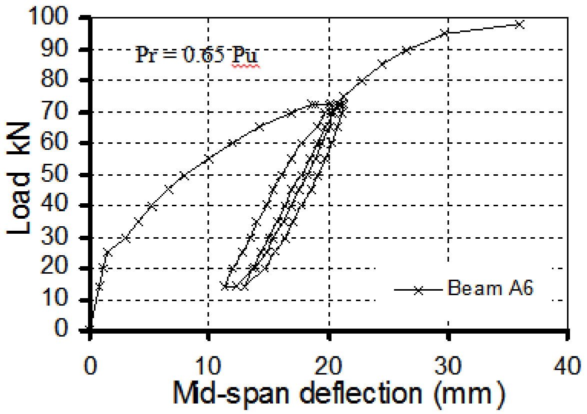

Fig. 5. Load mid-span deflection curve for beam A6 under repeated load.

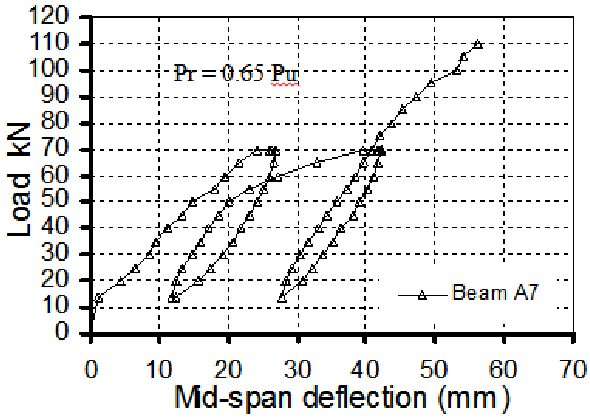

Fig. 6. Load mid-span deflection curve for beam A7 under repeated load.

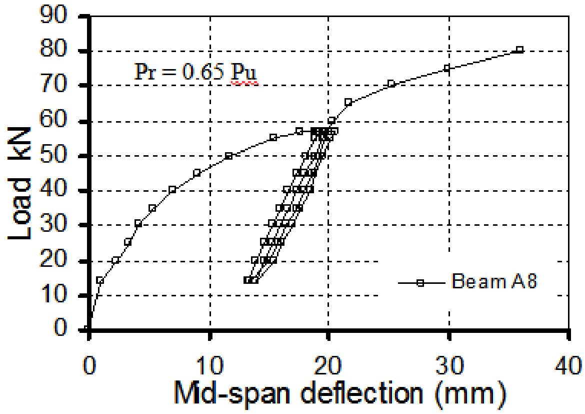

Fig. 7. Load mid-span deflection curve for beam A8 under repeated load.

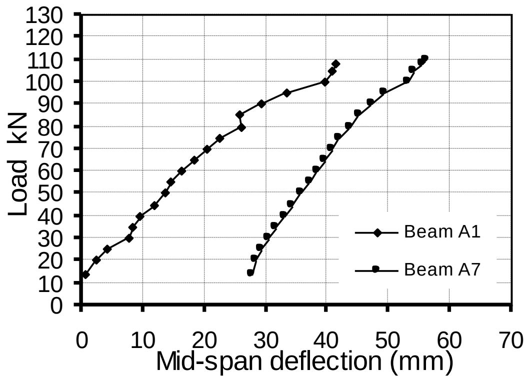

Fig. 8. Load mid-span deflection curves for beam A7 loaded up to failure after 10^6 cycles in comparison with identical beam A1 under static load.

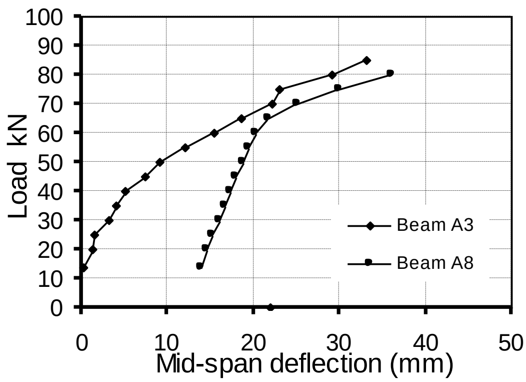

Fig. 9. Load mid-span deflection curves for beam A8 loaded up to failure after 10^6 cycles in comparison with identical beam A3 under static load.

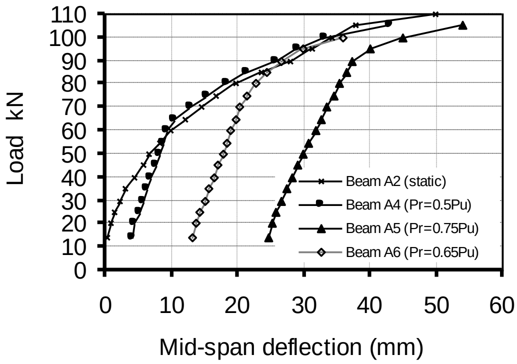

Fig. 10. Load mid-span deflection curves for beams A4, A5 and A6 loaded up to failure after 10^6 cycles in comparison with identical beam A2 under static load.

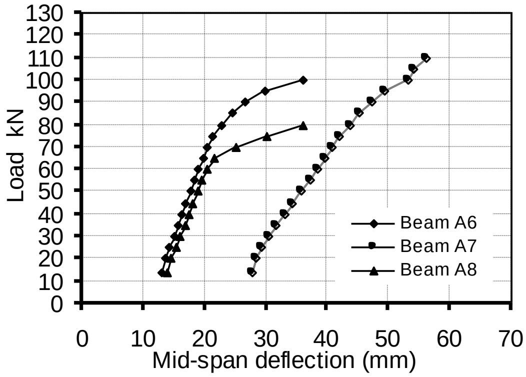

Fig. 11. Load mid-span deflection curves for beams A6, A7 and A8 loaded up to failure after 10^6 cycles.

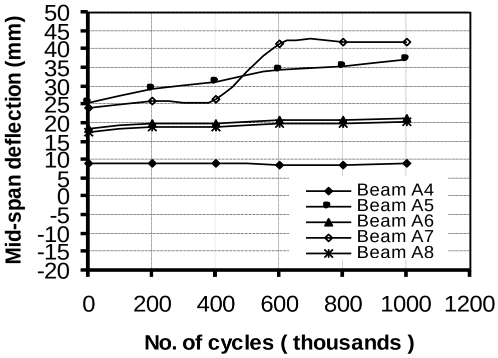

Fig. 12. Relation between maximum mid-span deflection and number of load cycles.

4.2. Crack patterns and mode of failure

The initiation and propagation of cracks for the different tested beams was observed visually with a magnifying glass. The pattern of cracks for concrete beams tested under static and repeated loading are given in plates 1, 2, 3 and 4 to 8, where cracks propagation at different stages of loading are recorded. It was noticed during testing of these beams in first static cycles that, the cracks were first initiated at the bottom side in the constant moment zone at a considerably low load levels and to a point higher than half of the beam depth. As the load increased, these cracks widened and propagated upward, later new cracks were created along the beam and the formed cracks propagated towards the point of load application. Comparison of cracks pattern at failure for beams A1, A2 and A3 tested under static loading with those beams A4, A5, A6, A7 and A8 tested under repeated loading showed that, the cracks width and their height in beams subjected to repeated loading were somewhat more than those for beams subjected to static loading.

In case of beams having different values of the $A_f/(A_f+A_s)$ ratio with the same reinforcement area, the number of cracks at failure for hybrid beams A6 having $A_f/(A_f+A_s)$ ratio equal to 0.56 and A8 having $A_f/(A_f+A_s)$ ratio equal to 0.39 was more than that of the Basalt FRP beam A7 having a bigger $A_f/(A_f+A_s)$ ratio equal to 1. With increasing the number of cycles, the cracks width and its lengths increased gradually for hybrid beams A6 and A8, while the growth of these cracks was quickly for Basalt FRP beam A7, see plates 6, 7 and 8. This confirmed the benefit of replacing part of Basalt FRP concrete beam's bars by steel bars in tension zone as they controlled the cracks propagation under repeated loading.

Table (4) gives the modes of failure for the different concrete beams tested under repeated loading. All beams failed in the same mode as for corresponding static one. The past history of repeated loading did not affect the mode of failure of these beams, which is similar to that of statically tested beams under virgin conditions; see plates 1, 2, 3 and 4 to 8.

Plate 1. Mode of failure of beam (A1)

Plate 2. Mode of failure of beam (A2)

Plate 3. Mode of failure of beam (A3)

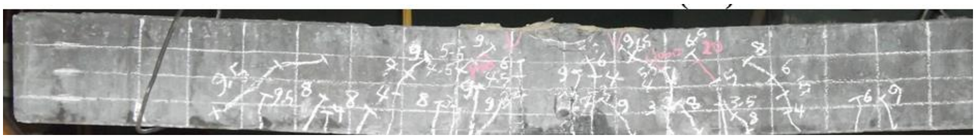

Plate 4. Mode of failure of beam (A4)

Plate 5. Mode of failure of beam (A5)

Plate 6. Mode of failure of beam (A6)

Plate 7. Mode of failure of beam (A7)

Plate 8. Mode of failure of beam (A8)

4.3. Cracking and ultimate loads

Table (4) includes also the cracking and the ultimate loads for different concrete beams tested under static and repeated loading. Comparison of cracking and ultimate loads for beams A1, A2 and A3 tested under static loading with those beams A4, A5, A6, A7 and A8 tested under repeated loading showed that, repeated loading has no tangible effect on the cracking and ultimate loads.

Regarding to the investigation of table (4), the cracking load was increased considerably with decreasing the $A_f /(A_f + A_s)$ ratio. The increasing of cracking load is mainly due to the fact that the existing of steel bars as tensile reinforcement to form hybrid beam delayed the appearance of cracks and increased the elastic stiffness of the cross section.

Table 4.
Test results for tested beams

Beam No.	f_{cu} N/mm^2	P_{cr} kN	P_u kN	P_u/P_{cr}	A_f / (A_f +A_s)	Mode of failure
A1	48.3	16	108	6.75	1	concrete crushed
A2	49.1	21	112	5.33	0.56	steel yield, concrete crushed
A3	50.2	20	88	4.4	0.39	steel yield, concrete crushed
A4	49.1	21	105	5	0.56	steel yield, concrete crushed
A5	49.1	25	107	4.28	0.56	steel yield, concrete crushed
A6	49.1	25	100	4	0.56	steel yield, concrete crushed
A7	48.3	14	110	7.86	1	concrete crushed
A8	50.2	20	78	3.9	0.39	steel yield, concrete crushed

Where: P_{cr} = Cracking load, P_u = Ultimate load.

5. Conclusions

The effect of static and repeated loading on the flexural behavior of concrete beams reinforced with hybrid reinforcements (Basalt FRP and steel rebars) or pure BFRP bars was experimentally investigated. Based on the results obtained in this work and within the range of variables considered here, the following conclusions can be drawn:

- The repeated loading has a slight effect on the ultimate load carrying capacity of the tested beams; however the deflection and cracks propagation increase significantly.
- Type of loading (static or repeated) has no effect on the mode of failure of beams but the cracking pattern due to static loadings was somewhat more segment and extensive than that due to repeated loading.
- The cracks width and their extent in hybrid beams is mainly controlled by steel rebars. Where, the maximum crack width and their extent increases as the A_f /(A_f +A_s) ratio increases.
- Adding low modulus BFRP rods with steel reinforcement decreases the obtained mid span deflection at any load level and increased the ultimate deflection.
- The cracking load was increased considerably with decreasing the A_f /(A_f +A_s) ratio, due to the fact that the existing of steel bars as tensile reinforcement to form hybrid beam delayed the appearance of cracks and increased the elastic stiffness of the cross section.

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سلوك الانحناء في الكمرات الخرسانية المسلحة بأسياخ من ألياف البازلت تحت الأحمال المتكررة

الملخص العربى

لقد أصبحت الأسياخ المصنوعة من الألياف البوليمارية هى الخيار العملي لمواد الإنشاء والتي يمكن أن تستخدم بدلاً من أسياخ الصلب في المباني الخرسانية. كما ان لها بعض المميزات مثل المقاومة للحريق والمغنطة والتوصيل للكهرباء والصدأ علاوة على خفة الوزن. أسياخ الألياف البوليمارية لها مقاومة للشد عالية. ولقد بدأ أخيراً في انتاج واستخدام أسياخ من ألياف البازلت. وحيث أن لهذه الأسياخ معاير مرونة منخفض مقارنة بالصلب ولا توجد لها نقطة خضوع قبل الوصول للمقاومة القصوى مما يؤثر سلباً على سلوك الانحناء وجساءة العنصر الخرساني.

لذلك فإن هدف هذا البحث هو دراسة تأثير إضافة أسياخ صلب إلى القطاع المسلح بأسياخ من ألياف البازلت تحت تأثير الاحمال المتكررة لتحسين سلوك الإنحناء في هذه الكمرات من ناحية الجساءة وشكل الإنهيار.

في هذا البحث تم عمل دراسة عملية على سلوك ثمانية كمرات خرسانية مسلحة إما بأسياخ من ألياف البازلت فقط أو خليط منهما, وكانت هذه الكمرات ذات أبعاد ثابتة حيث بلغ طولها 2050مم وعرضها 150مم وارتفاعها 200مم. تم أخذ عدة متغيرات في الاعتبار مثل نسبة مساحة مقطع أسياخ ألياف البازلت إلى المساحة الكلية لأسياخ منطقة الشد في القطاع (أسياخ الصلب وأسياخ ألياف البازلت) وذلك على كل من قدرة تحمل وتشكل وطراز الانهيار لهذه الكمرات المختبرة. النتائج أظهرت التأثير المفيد لإضافة أسياخ الصلب على قدرة تحمل هذه الكمرات وتحسين سلوكها تحت تأثير الأحمال المتكررة.