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Flexural Performance of Steel Fiber Concrete Beams Reinforced with Hybrid Schemes

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Abstract: The flexural behavior of concrete beams reinforced with hybrid reinforcing schemes is investigated experimentally in this work. The effects of steel fibers inclusion on the flexural behavior of concrete beams reinforced using hybrid schemes were investigated using four half-scale beams. The steel fibers content (0.00%, 0.50%, and 1.00%) was the main important parameter. The experimental results demonstrated that steel fibers inclusion significantly improved the ultimate load, stiffness, and toughness of concrete beams. Load capacity was enhanced by 13% and 21% for steel fibers volume ratios of 0.50% and 1.00%, respectively. Toughness improvements were 97.7% and 161% for steel fibers volume ratios of 0.50% and 1.00%, respectively. A non-linear finite element analysis (NLFEA) was performed to simulate the flexural behavior of RC beams reinforced with hybrid schemes. The load-deflection responses and crack patterns of experimental specimens and numerical models were compared. The comparison showed a good agreement between the experimental and numerical results. The overall average value of the ratio between the experimental flexural capacities to the predicted capacities is about 0.94 and the standard deviation was of 0.028.

Keywords: Hybrid schemes, Steel fibers, Finite element, Toughness.

1. Introduction

Researchers have been interested in exploring the efficiency of using fiber-reinforced polymers (FRP) as a good alternative to traditional steel in RC structures over the last few decades since it can enhance the sustainability of concrete structures and increase the corrosion resistance. FRP also has the advantages of being lightweight and having a higher tensile strength, thus the capacity of RC sections can be raised adequately.

Many researchers have already investigated the flexural behavior of beams reinforced with FRP bars, both experimentally and statistically [1–4]. The mid-span deflection, crack width, and flexural capacity have been measured and discussed. The reinforcement ratio was the main parameter. It was discovered that raising the reinforcing ratio of FRP reduces crack width. The failure mode was mostly due to concrete crushing if the reinforcement ratio was more than balanced ration and due to FRP bar rupture if the reinforcement ratio was less than balance ratio. Over-reinforced FRP sections may be more ductile than under-reinforced FRP sections as FRP bars have linear behavior till failure. FRP-reinforced beams may have greater flexural capacity than steel-reinforced beams, but they may also have fewer warnings before failure and greater mid-span deflection.

The enhancement of FRP reinforced beams has been investigated by using hybrid schemes [6–13]. An experimental program was developed to investigate the flexural behavior of concrete continuous beams reinforced with hybrid schemes [12]. The tested beams' deflection, cracking load, and flexural moment capacity were also investigated. The important parameters were the reinforcement ratio in the section and the steel-to-FRP area ratio. It was discovered that the hybrid reinforced beams failure was ductile due to concrete crushing after reinforcing steel yielding, resulting in an adequate level of warnings before failure. The presence of steel bars in concrete beams increased stiffness, decreased mid-span deflection and fracture propagation, and increased ductility. Increased reinforcement (steel or FRP bars) increased stiffness, however, more steel bars resulted in decreased load capacity following steel yielding while increasing FRP bars resulted in less ductile behavior. To improve serviceability, a smaller portion of FRP would be used, although the improvement in section capacity would be restricted.

There is another way to mix steel with E-glass fiber-reinforced polymers (GFRP) by using hybrid bars, in which a steel bar is located in the core and wrapped in FRP to create a hybrid bar [14]. They conducted an experimental investigation of the behavior of concrete beams reinforced with hybrid bars. The reinforcement bar type (steel, GFRP, or hybrid) and reinforcement ratios were the most important parameters. The cracking load, stiffness, toughness, and flexural capacity were discussed and studied. Using hybrid bars enhanced the first crack load and ultimate load substantially. This occurred due to the existence of an outer layer of GFRP in the bar which has a higher tensile strength than steel bars. A significant improvement was observed in the ductility of beams due to the existence of an inner layer of steel in the bars which provides reasonable level of warnings by yielding before failure.

Some researchers have attempted to enhance the flexural behavior of FRP reinforced beams by improving the properties of the concrete matrix by including different types of fibers [16–25]. The addition of fibers to the concrete matrix raises the ductility index, reduces cracks propagation, and increases tensile strength, therefore increasing the stiffness of the element. The flexural behavior of fiber concrete beams reinforced with FRP bars was studied. [15]. The thickness of the fiber reinforced layer, the volume fraction of steel fibers, and the FRP reinforcement ratio were the main parameters. It was determined that increasing the fiber reinforced thickness reduces the mid-span deflection of concrete beams that meet serviceability criteria and minimizes the ratio between the ultimate and service load. The insertion of steel fibers in the tension zone was an effective method for minimizing crack width and deflection. However, it reduced ductility, resulting in failure due to FRP bar rupture caused by tensile stress concentration induced by steel fibers in tension zone. Adding steel fibers to the compression zone improves beam ductility.

The hybrid reinforcement definitely has a significant impact on improving the ductility of the FRP-reinforced concrete section as well as increasing the stiffness to meet serviceability requirements. However, in order to reap these benefits, a high steel to FRP ratio is required. As a result, it is not able to get the full section capacity. Adding steel fibers to the compression zone of a concrete section increases ductility, whilst adding steel fibers to the tension zone increases the stiffness and minimizes crack width and crack propagation.

The aim of this work is to investigate the flexural behavior of steel fiber- concrete beams reinforced with hybrid schemes in order to increase the FRP reinforcement in the section dependent on the steel fibers for enhancing the stiffness and ductility of the beams. The main parameters were the ratio between steel and FRP reinforcement and the steel fiber volume ratio of the concrete section. The load-carrying capacity, first cracking load, load-deflection responses, crack pattern, and failure modes were all reviewed.

2. TEST POGRAM

2.1 Mechanical Properties of GFRP bars and steel fibers

The GFRP bars were locally manufactured using resin and glass fiber roving. Plastic molds with were created at a specific workshop for manufacture. As illustrated in Fig. 1, the ribbed bars have a diameter of 10, 12 mm.

The tensile strength and mechanical characteristics of GFRP bars were experimentally investigated. To improve the bond between the GFRP bars and the concrete, the outside surface of the bars was deformed. The mechanical characteristics of GFRP bars are illustrated here in Table 1.

Fig 1. Produced GFRP and Steel Bars

TABLE 1. Properties of Glass Fiber Reinforced Bars (GFRP).

Diameter (mm)	Tensile strength (MPa)	Elastic Modulus (GPa)
10	1035.0	46.0
12	960.0	42.6

Corrugated steel fibers were used in the Steel fiber reinforced concrete. The mechanical characteristics of steel fibers are as follows:

The mechanical properties of steel fibers were provided by supplier as illustrated are shown in Table 2.

The compressive strength of concrete depended on the quality of the constituent materials. After 28 days of curing, the target cubic compressive strength was 30 MPa. The proportions of concrete constituents are shown in Table 3.

2.2 Test specimens

Four concrete beams reinforced with steel or hybrid schemes and containing various contents of steel fibers were designed as simply supported span with an adequate amount of longitudinal and using stirrups from mild steel. Two beams labeled (B1 and B2) don't include steel fibers to present the control specimens. Another specimen include 0.50 % steel fibers volume ratio (B3). The last specimen was poured with S.F volume ratio of 1.00% (B4).

Fig 2. Wooden form and reinforcement of the concrete beams

The used reinforcement in all specimens was hybrid schemes except for the specimen B1 that was reinforced with steel bars only. The details of the experimental program are shown in Fig. 3, and listed in Table 4.

TABLE 2. Properties of Steel fibers (SF).

Type of S.F	Tensile strength *(MPa)*	Elastic Modulus *(GPa)*	Length *(mm)*	Diameter *(mm)*	Length-diameter ratio
Corrugated	1000	200	50	1	50

TABLE 3. Quantity Required of Concrete Mix Proportions for $1m^3$ (kg).

Cement	Sand	Coarse aggregate	water
350	680	1400	175

TABLE 4. Details of the Tested Beams.

Beam	V_f	Bottom RFT		Bottom RFT ratio			Stirrups	Top RFT
		Af	As	ρ_f	ρ_s	ρ_t		
B1	0.0%	---	4T10	0.00%	0.94 %	0.94 %	ϕ8 / 100	2T10
B2	0.0%	2G10	2T10	0.47 %	0.47 %	0.94 %	ϕ8 / 100	2T10
B3	0.5%	2G10	2T10	0.47 %	0.47 %	0.94 %	ϕ8 / 100	2T10
B4	1.0%	2G12	2T10	0.67 %	0.47 %	1.14 %	ϕ8 / 100	2T10

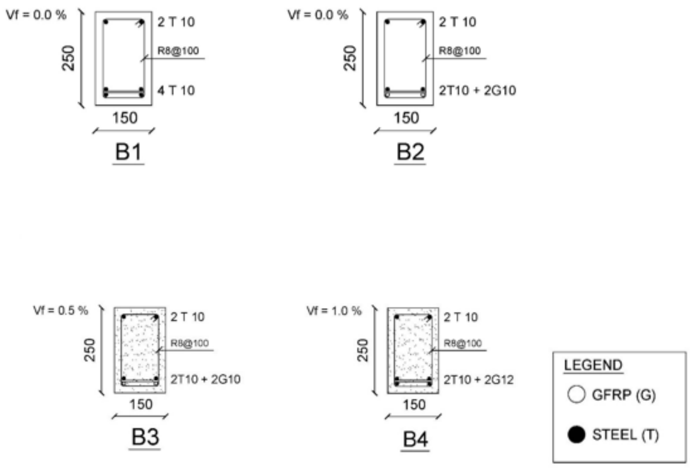


Fig 3. The geometry and details of the tested beams

2.3 Test setup

A machine of 1000 KN capacity was used to test the beams. Two loads separated by 400 mm were symmetric about the beam center. Three linear variable differential transformers (LVDTs) was fixed at the midpoint of beams and the applied loads to record deflection. The beam under loading machine are illustrated in Fig. 4.

Fig 4. Typical Beam during Testing

3. EXPERIMENTAL RESULTS AND DISCUSSION

Complete analysis of results is important to study the flexural response and respective failure mechanism associated with the static loading of tested beams. It is also important to study the effect of steel fibers inclusion with different volume ratios on the flexural behavior of these beams.

3.1 Crack load and ultimate load

The cracking load (pcr) was recorded for all beams by inspecting the beam until the creation of the first crack and recording the associated load. Each beam's ultimate load (pu) was also measured. The observed test results for Tested beams are summarized in Table 5.

There was no improvement in the first crack load when using Hybrid schemes with the same reinforcement ratio in the longitudinal reinforcement in beam B2 compared with B1. However, when hybrid schemes with the same reinforcement ratio were used, the ultimate load was enhanced by 8% in B2.

The use of 0.50% steel fiber volume improved the first crack load by 12.5% more than specimens B2. In addition, the improvement in the maximum load was 12% for B3. For specimen B4 with 1.00% steel fibers volume ratio, the cracking load was enhanced by 25% compared with specimen B2. Also the enhancement in load carrying capacity was 21% for specimen B4.

TABLE 5. Experimental Results of the Tested Beams.

Beam	V_f (%)	Experimental Test Results						
		P_{cr} (KN)	P_y (KN)	δ_y (mm)	P_u (KN)	δ_u (mm)	K (KN /mm)	DF
B1	0.00	17	75.5	12.14	82.2	60.75	6.21	5.00
B2	0.00	16	55.2	12.12	89.0	59.60	4.55	4.91
B3	0.50	18	52.2	9.78	100.2	97.44	5.33	9.96
B4	1.00	20	55.9	9.68	114.2	94.57	5.77	9.76

Where

δ_y: The deflection at yielding level.

δ_u: The deflection at ultimate level.

P_u : The load at ultimate level.

P_y : The load at yielding level.

K: The initial stiffness

There was no improvement in the first crack load when using Hybrid schemes with the same reinforcement ratio in the longitudinal reinforcement in beam B2 compared with B1. However, when hybrid schemes with the same reinforcement ratio were used, the ultimate load was enhanced by 8% in B2.

The use of 0.50% steel fiber volume improved the first crack load by 12.5% more than specimens B2. In addition, the improvement in the maximum load was 12% for B3. For specimen B4 with 1.00% steel fibers volume ratio, the cracking load was enhanced by 25% compared with specimen B2. Also the enhancement in load carrying capacity was 21% for specimen B4.

The enhancement in the cracking load is attributed to the presence of steel fibers in the tension zone in inhibiting crack propagation and decreasing crack width. Also, increasing the steel fiber ratio improved maximum load by improving concrete ductility due to the presence of steel fibers in the compression zone, resulting in a higher level of warnings before collapse. As a result, the addition of steel fibers to beams reinforced using hybrid schemes greatly enhances the cracking load and ultimate load.

3.2 Load-deflection curves

The maximum deflection for B2 was less than that of B1, but the failure load for B2 was more than that of B1.These results showed that the ductility of beams reinforced with hybrid schemes is decreased because of the use of hybrid bars. When steel fibers were included in the concrete matrix with 0.50% content, the maximum deflection in B3 is much higher than that of B1. Also the ultimate load was slightly enhanced. When the steel fiber content was increased to 1.00% in specimen B4, the maximum deflection was significantly increased. The experimental load-deflection relationships are illustrated in Fig. 5. The efficiency of steel fiber addition in improving the ductility of the concrete beams reinforced with hybrid schemes was confirmed by the experimental results. Based on the load-deflection curves, the following measurements can be evaluated as follows:

3.2.1 Initial Stiffness

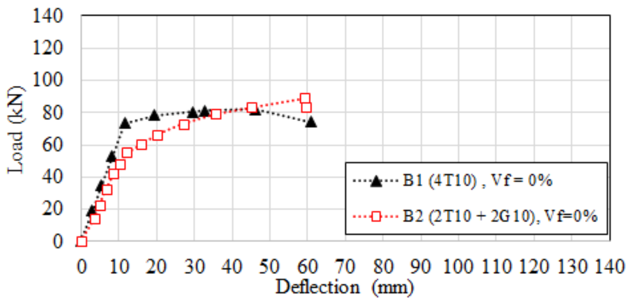
Stiffness is defined as the ratio between the load at yield point (P_y) to the corresponding displacement (δ_y). The stiffness of the specimen B2 was decreased by 27% compared with specimen B1. The stiffness of B3 was improved by 17% compared with B2 with same reinforcement without steel fiber inclusion. For Specimen B4, the stiffness was improved by 25% compared with beam B2.

3.2.2 Energy Absorption (Toughness)

Toughness is defined as the area under the load-deflection curve depending on the ultimate load (P_u) and the corresponding deflection (δ_u); so it is a good indication to the ductility of the beam. Compared with B1, the toughness of B2 was decreased by 7.4%. The toughness of beams B3 and B4 was enhanced by 97.7% and 123% respectively. It can be concluded that adding steel fibers to the concrete matrix of hybrid reinforced beams significantly enhance the energy absorption. Also the enhancement ratio of the toughness increases by increasing the fiber volume ratio from 0.50% to 1.00%.

3.2.3 Ductility Factor

Ductility factor is defined as the ratio between the deflection at failure point (δ_u) to deflection at yield point (δ_y). Compared with specimen B1, the ductility factor of specimen B2 was reduced by 16%. For specimen B3, ductility factor was enhanced by 103% compared with beams B2. For specimen B4, ductility factor was increased by 132% compared with beams B2. It can be said that the flexural behavior of concrete beams reinforced with hybrid schemes is significantly improved by steel fibers inclusion in concrete mix.



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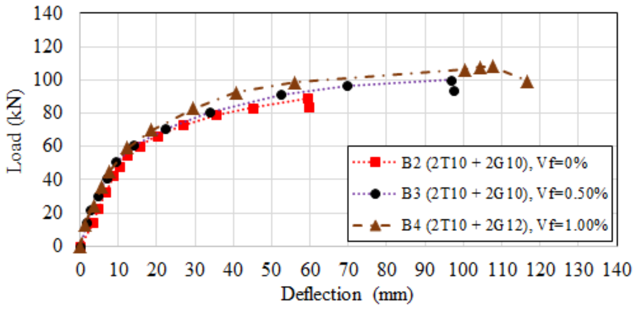


(b)

Fig 5. Load-Deflection curves of the Tested beams.

3.3 Failure modes and cracks pattern

One of the most important ways for describing the failure mechanism and understanding how the failure happened, as well as examining the impact of the parameters on the behavior of the tested beam, is to track the route of cracks and record the associated loads at various loading levels. The crack patterns of the tested beams are shown in Fig .7.

Flexural failure of tested beams was caused by yielding of steel bars followed by concrete crushing prior to GFRP bar rapture. Using hybrid methods in beam B2 accelerated the formation of the first crack when compared to beam B1 reinforced exclusively with steel bars. At the failure level the using of hybrid schemes led to increasing the propagation and width of visual cracks. However, using steel fibers with 0.50% volume ratio in B3 delayed the appearance of first crack compared with beams not containing steel fibers in specimen B2, increased the ductility and energy absorption of beams and led to stapling cracks and decrease their propagation resulting in the load capacity of beams and preventing the occurrence of sudden explosive failure under the static loads. For specimen B4, raising the steel fiber volume ratio from 0.50% to 1.00% delayed the formation of the first crack and increased the ductility and toughness of the beams, improving the load capacity of the beams without rapid explosive failure.

4. NON-LINEAR FINITE ELEMENT ANALYSIS

ANSYS V15 has been used to simulate the flexural behavior of SFRC beams reinforced with hybrid schemes. The main guide used to study the flexural behavior of the tested specimens was the load- deflection response as it includes many important parameters such as cracking load, load carrying capacity, maximum deflection, and ductility factors. Comparing the load – deflection curves of the experimental results with numerical results is an effective method to validate the NLFEA modelling .

4.1 Finite element geometric and material idealization

The concrete in the tested beams was simulated using solid 65 element which facilitates the ability of concrete crushing in zones of compression stresses and cracking in zones of tensile stresses. The content of the steel fibers was defined through the volume ratio and number of defined material used to represent the steel fibers. The volume ratio was calculated by dividing the steel fibers volume by the volume of the solid element. The used stress-strain relationship is hongestad equation which accurately represent the model of fibrous and non-fibrous concrete in compression. Steel and GFRP longitudinal reinforcement and steel stirrups were simulated using Link 180 element. The bilinear stress–strain curve was adopted for steel reinforcement in tension and compression, while a linear elastic behavior was used for the GFRP bars.

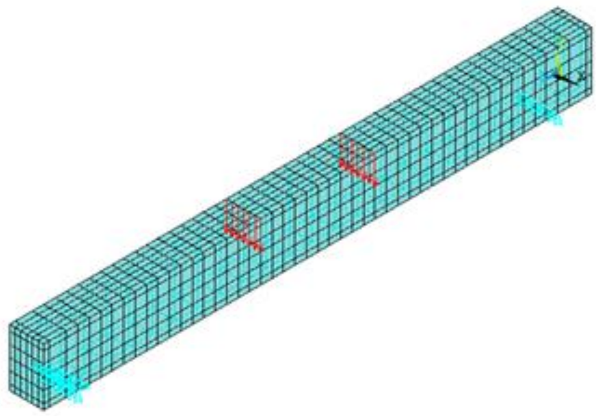


Fig 6. Finite Element Model for Tested Beams.

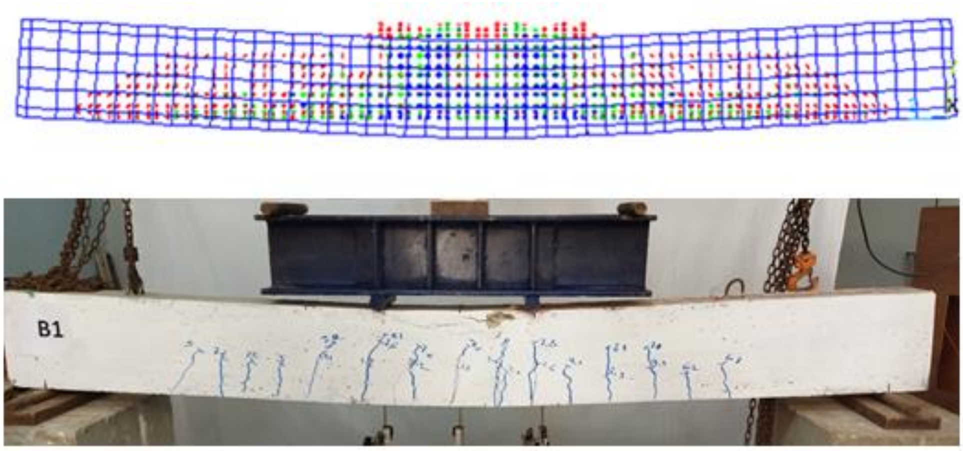
4.2 Non-Linear Finite element model verification

4.2.1 Validation of crack patterns

The results from NLFEA are compared with the experimental results of the tested specimens. The first crack was observed to be a vertical crack in the moment zone. By increasing the loading level, new cracks were formed between the two loads and inclined cracks were formed between the point load and the support (shear zone). The predicted crack patterns from NLFEA are compared with experimental crack patterns as shown in Fig.7. There is a good agreement between experimental and numerical crack patterns of tested beams.

4.2.2 Validation of load-deflection curves

The comparison between experimental and numerical load-deflection curves for fibrous and non-fibrous concrete beams reinforced with hybrid schemes are shown in Fig.8. Good agreement is observed between the numerical and experimental results. The load-deflection curve resulting from numerical results is too close to experimental results in the linear stage of the curve. The comparison between numerical and experimental results is illustrated in Table 6.



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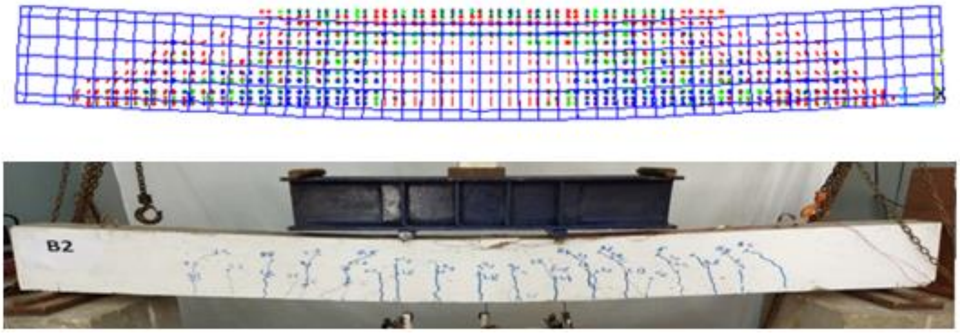

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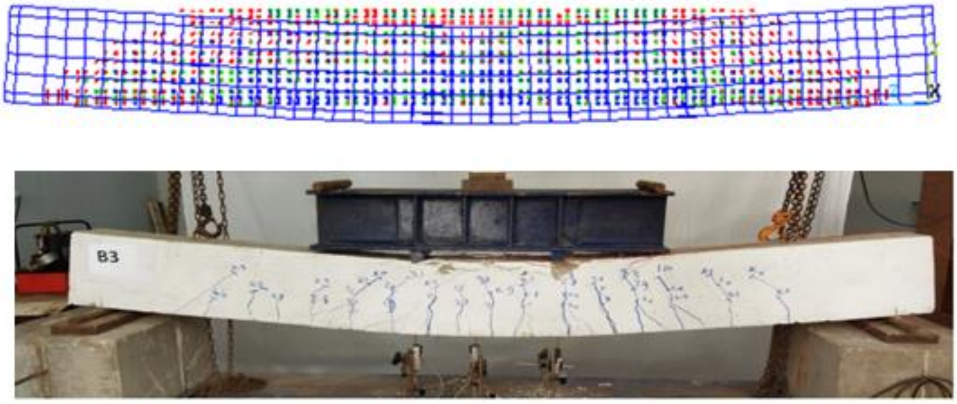

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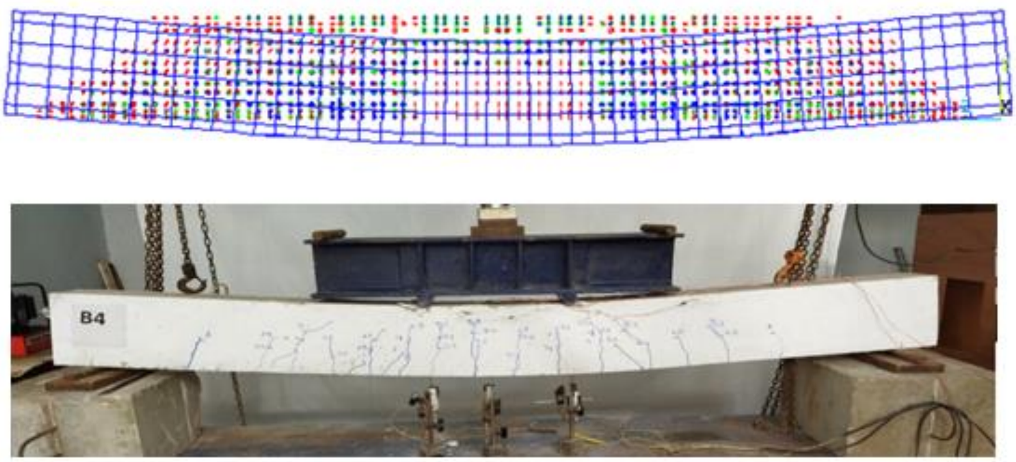
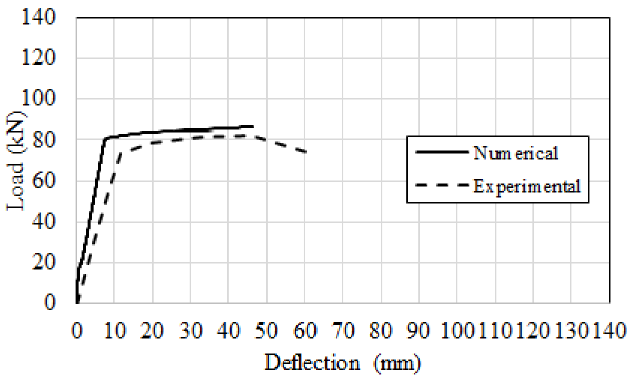


(B4)

Fig 7. Predicted Crack Pattern for Tested Beams.

TABLE 6. Comparison between the Experimental Tests results and the Numerical results.

Beam No	P_y (EXP kN	P_u (EXP kN	P_y (FE) kN	Pu (FE) kN	Δ_y (EXP mm	Δ_u (EXP mm	Δ_y (FE) mm	Δ_u (FE) mm	$\frac{P_{y(EXP)}}{P_{y(FE)}}$	$\frac{P_{u(EXP)}}{P_{u(FE)}}$	$\frac{\Delta_{y(EXP)}}{\Delta_{y(FE)}}$	$\frac{\Delta_{u(EXP)}}{\Delta_{u(FE)}}$
B1	75.5	82.2	81.3	86.4	12.14	60.75	8.87	46.1	0.92	0.951	1.36	1.31
B2	55.2	89.0	60.7	94.2	12.12	59.6	12.9	48.9	0.908	0.944	0.939	1.21
B3	52.2	100.2	50.7	106	9.78	97.44	9.42	81.1	1.028	0.93	1.038	1.20
B4	55.9	114.2	57.7	124	9.68	94.5	9.55	78.4	0.967	0.915	1.013	1.20
						Average			0.973	0.942	1.10	1.23
						St. deviation			0.048	0.028	0.15	0.09



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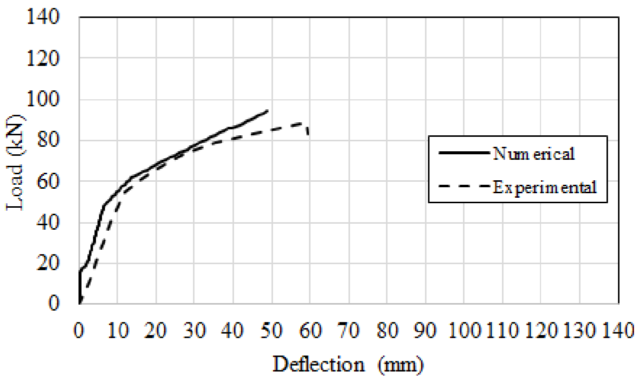

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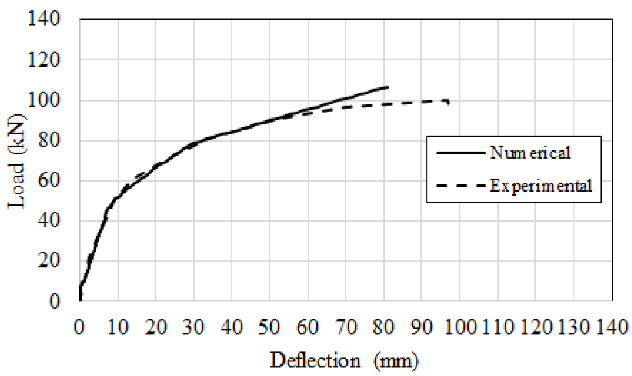

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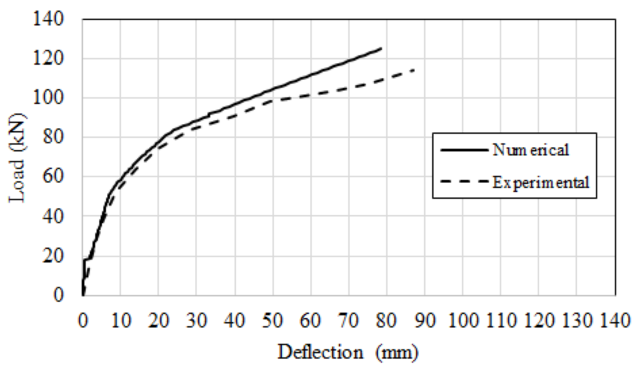

(B4)

Fig 8. Comparison between experimental and numerical load-deflection curves for tested beams

5. CONCLOSION

The flexural behavior of steel fiber concrete beams reinforced with hybrid scheme (steel + GFRP) was discussed. Based on the experimental results of tested beams, the main conclusion points may be listed as follows:

1- Adding steel fibers to concrete improves its mechanical characteristics, delays the appearance of the first crack, and increases the load capacity.
2- Using the hybrid scheme in concrete beams increases the load carrying capacity but it reduces the stiffness, ductility and energy absorption of beams. The reduction in stiffness was 27% in beam B2 comparing with beam B1. Also the toughness of beam B2 was decreased by 7.4%.
3- The load capacity was enhanced by 13% and 21% for steel fiber content of 0.50% and 1.00% respectively, and the improvement in stiffness was 17% and 21% for steel fiber content of 0.50% and 1.00% respectively. The ductility factor was enhanced by 65% and 132% for steel fiber content of 0.50% and 1.00% respectively.
4- The first crack appearance was delayed due to increasing steel fiber content. The first crack load was increased by 12.5% and 19% for steel fiber content of 0.50% and 1.00%.

5- The failure of the beams was ductile by steel yielding before concrete crushing and finally rapture of GFRP bars.
6- A good agreement was achieved between the experimental results and results predicted using NLFEA models for crack patterns and load deflection responses. The overall average value of the ratio between the experimental flexural capacities to the predicted capacities is about 0.94 and the standard deviation was of 0.028.

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