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FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH HYBRID STEEL- FRP REINFORCEMENTS BY USING NEAR SURFACE MOUNTED TECHNIQUE

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This paper investigated the behavior of reinforced concrete (RC) beams of near surface mounted (NSM) strengthening technique with using steel bar and hybrid steel bar. The effects of NSM reinforcement and load patterns on the flexural behavior and ductility of the RC beams have been studied. A four-point bending test was carried out on five reinforced concrete beams divided into two groups. The first group was tested under the effect of static load, whereas the second group was tested under repeated load. The experimental results are reported regarding the failure mode, flexural strength, load-deflection response, cracking behavior, and ductility. These results showed that strengthening of concrete beams with NSM steel bar increased the yielding and ultimate loads by about 28.6% and 28.5% respectively as compared to control beam, whereas the yielding and ultimate load increased to 33% and 35.7% over the control beam when strengthened with hybrid NSM steel bar. The ductility index of the control beam was equal to 2.6, this value increased to about 24.6% and 52.3% of the NSM steel bar and NSM hybrid steel bar strengthened beams respectively. The repeated load decreased the load capacity of the strengthened hybrid beams by about 65%, whereas the mid-span deflection is nearly the same.

Keywords: near surface mounted technique, hybrid reinforcements, ductility index

1 INTRODUCTION

Research efforts have been focused on developing effective and affordable materials for repairing harmed structures as a result of the damage to structural elements such as buildings and bridges caused by structural deficiencies (materials degrading or aging, earthquakes, or poor maintenance) [1].

The most common techniques that are used to strengthen, rehabilitation or repairing of reinforced concrete members are Surface Bonding (SB) technique and the Near Surface Mounted (NSM) technique [2]. Although, the strengthening by SB technique represents the popular strengthening technique, but the shortcomings of this technique are de-bonding failure and weak resistance to the harmful environmental conditions, so that NSM technique surpass the SB technique in strengthening of the concrete structures [3].

Regarding to the overview of the previous researches, several studies focused on surface bonding of Fiber Reinforced Polymer (FRP) to the surface of the concrete beams. This strengthening technique improves stiffness and enhances the load bearing capacity [4, 5, 6, and 7]. The shortcomings associated with the using FRP surface bonding is that the FRP has linear stress-strain characteristics up to failure and lack of yield plateau which have a negative impact on the overall ductility of the strengthened reinforced concrete elements. In addition, The FRP may fail without warning due to FRP de-bonding or rupture of the FRP sheets [8].

The NSM strengthening technique is accomplished by inserting FRP reinforcements into precut grooves in the concrete cover (tension region) of the concrete member. This method showed to be simple and improves the bonding of the mounted FRP reinforcements to the surrounded concrete [9].

Several researchers studied the behavior of concrete beams reinforced with hybrid composites to increase the stiffness and ductility of the strengthened members.

These hybrid materials are made up of various types of materials such as glass fiber, aramid fiber, steel mesh of galvanized, aluminum alloys, and carbon fiber (CFRP) composites that fail at different levels of strains during loading, allowing composites to fail gradually [10, 11, 12, 13, 14, 15]. They observed that the beams strengthened with the developed fabric exhibited higher ductility indexes than those strengthened with one type of FRP material.

Based on the previous investigations, there were little researches investigations the behavior of concrete beams strengthened with hybrid steel-CFRP composite. Accordingly, an experimental program was investigated by casting and testing reinforced concrete beams un-strengthened and strengthened using NSM Hybrid reinforcements.

2 EXPERIMENTAL PROGRAMS

The experimental investigations comprise the material strength test and beam flexural behavior test.

2.1 Material properties

The yield strength of the steel bars that were used for flexural reinforcement, shear reinforcement, and steel NSM reinforcement according to standard tensile test (ASTM A370) (15) was 400MPa. The compressive strength test was conducted in accordance with ASTM C39 [16]. The compressive strength of the concrete at 28-day is 25 MPa. The fibers used for strengthening are unidirectional carbon fiber reinforced polymer sheet, CFRP (SikaWrap230C) [17]. The major characteristics of the strengthening materials used herein in the tests represented by FRP manufactured are in table 1. The epoxy adhesive that was used in the strengthen beams are (Sikadur®-300) [18].

Table 1. FRP Fabric Mechanical Properties

Fibers Tensile Strength [MPa]	Fibers Tensile E-modulus of [MPa]	Strain of Fibers at Break %	Fabric Design Thickness [mm]	Fiber orientation
4100	231000	1.7	0.12	unidirectional

2.2 Details of tested beams

Five reinforced concrete beams of 150mm height and 100mm width with a 900mm clear span were casted. All beams were reinforced with 2-Ø8mm diameter steel bars in tension and compression face with a reinforcement ratio equal to 85.2%. Shear reinforcements of Ø8 mm reinforcing bar stirrups were distributed along the shear span region at a center to center spacing of 50mm as shown in fig. 1.

The experimental program was divided into two groups. The first group consists of control beam (CB), strengthened beam by NSM steel bar (SSB), and strengthened beams by NSM hybrid steel bar (SHB) which were statically tested under four points loading up to failure. The second group consists of two beams strengthened with NSM hybrid bar (SHB1 and SHB2) which were tested under repeated loading up to failure.

SSB was strengthened with an 8mm diameter steel bar, while the rest of the beams (SHB, SHB1, and SHB2) were strengthened by 8mm diameter hybrid bar (steel bar wrapped by CFRP sheet), beam SHB1 was tested under static loading up to 12.5kN (50% of yielding load) and unloading to zero after that a repeating load of 2.5kN increment gradually increased until failure, while Beam SBH2 was tested under static load up to 12.5kN after that a repeating load of 2.5kN increment gradually increased for five cycles of loading-unloading up to a cycle of 7.5kN, then a static load was applied until failure. The mid-span deflection was measured during the experimental test. Table 2 summarizes the details of the tested beams.

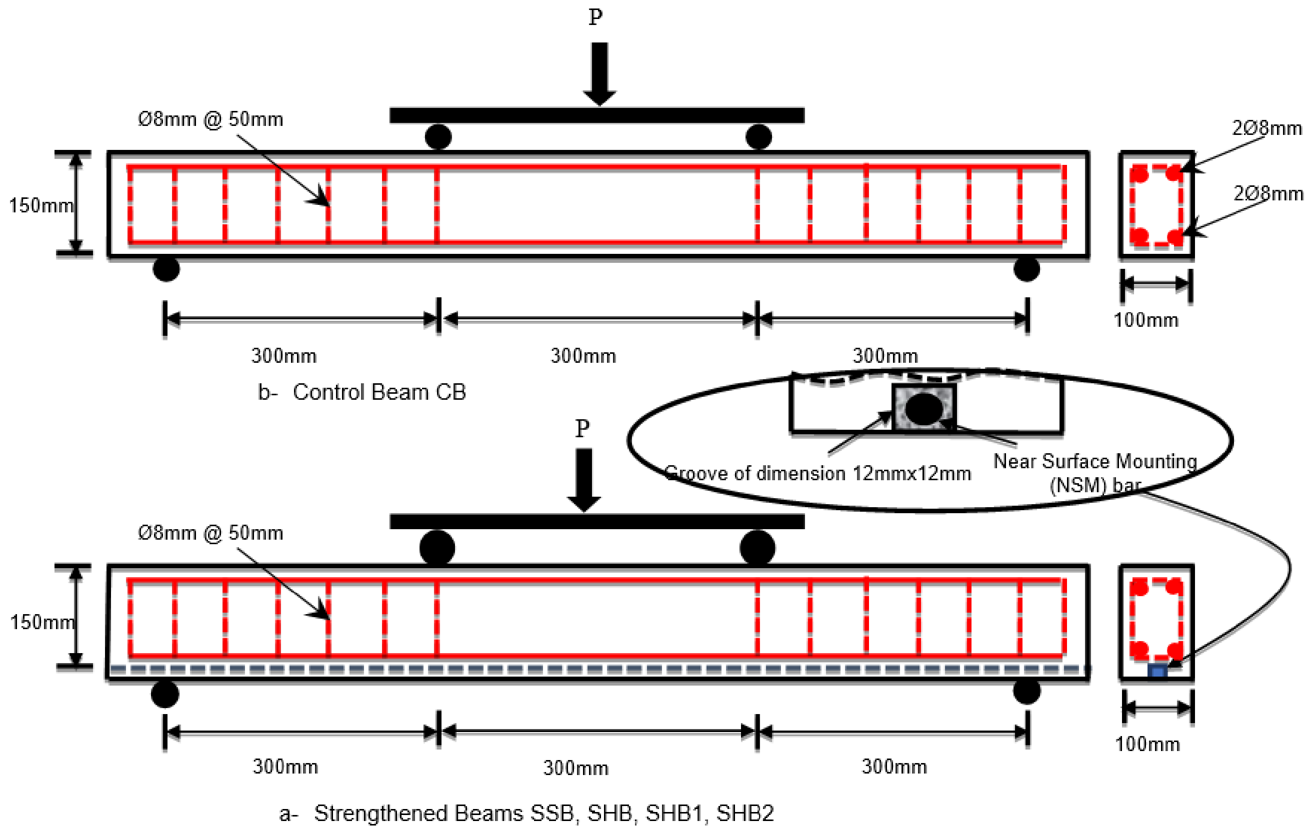

Fig. 1. Reinforced Concrete Beam Specimens, a-Control Beam CB, b-Strengthened Beams SSB, SHB, SHB1, SHB2

Table 2. Configuration of the tested beams

Beam Code	Type of strengthening reinforcements	Loading Pattern
CB	Control Beam	Static

Beam Code	Type of strengthening reinforcements	Loading Pattern
SSB	Steel reinforcement	Static
SHB	Hybrid Steel-CFRP reinforcement	Static
SHB1	Hybrid Steel-CFRP reinforcement	Repeated
SHB2	Hybrid Steel-CFRP reinforcement	Repeated

2.3 Strengthening Procedure

The strengthening procedure conducted in the present study consists the following:

1. Making a square slot of 12 mm dimension at the bottom surface during casting of the beam (fig. 2a).
2. After curing the beams, surface preparation and cleaning by acetone were conducted on slots.
3. Two components epoxy adhesive was applied according to the manufacturer's recommendations to fill the slots, while a steel bar or a developed hybrid bar is placed through the slot as shown in fig. 2b.
4. Excessive epoxy adhesive was removed using a spatula.
5. The beams let to cure based on the recommendation of the manufacturer [18].

(a)

(b)

Fig. 2. (a) Cutting A square Slot at the Bottom of the Beam, (b) Finishing of the Strengthening Technique

3 EXPERIMENTAL RESULTS

3.1 Load-Deflection Relationship

Fig. 3 shows the load-deflection relationship of CB, SSB, and SHB. CB shows a traditional flexural behavior until failure. A linear relation between load and deflection was observed until a first cracking load occurred at 7.5 kN with a mid-span deflection equal to about 0.95 mm. By increasing the load, the trend of the curve changed until yielding of the tensile steel reinforcement which occurred at 25kN with a mid-span deflection equal to 5mm. The failure of the beam was typically as under-reinforced section by progressive increasing in the mid-span deflection until crushing of concrete at an ultimate load equal to 31.5 kN with a mid-span deflection equal to 13 mm.

By comparing the CB with the strengthened beams (SSB and SHB), it was observed that the beam that was strengthened by developed hybrid bar (SHB) surpass on the traditional strengthened beam SSB in improving the initial stiffness, yield load, and ultimate load. The cracking load is nearly the same for all tested beams, while the yielding load increased to 28.6% and 33% of SSB and SHB respectively as compared to yielding load of the CB. The increasing in yielding load of the SHB over traditional strengthened beam is attributed to the improvement in the stress-strain behavior of the hybrid reinforcement. The ultimate load of SSB and SHB increased to about 28.5% and 35.7% as compared to ultimate load of CB respectively. The ductility index of CB, SSB, and SHB is equal to 2.6, 3.45, 5.45 respectively. The ductility index of SSB and SHB increased to about 24.6% and 52.3% over the ductility of CB respectively. Accordingly, the ductility index of SHB equals to two times the ductility index of the SSB. The higher ductility coefficient of SHB is attributed to the lower mid-span deflection at yielding of the tensile steel reinforcement and higher mid-span deflection at failure.

According to the results of the experiments, using hybrid steel-FRP bar improved the ductility of the strengthened beams, which resulted in improved structural behavior of the concrete members and economical material utilization.

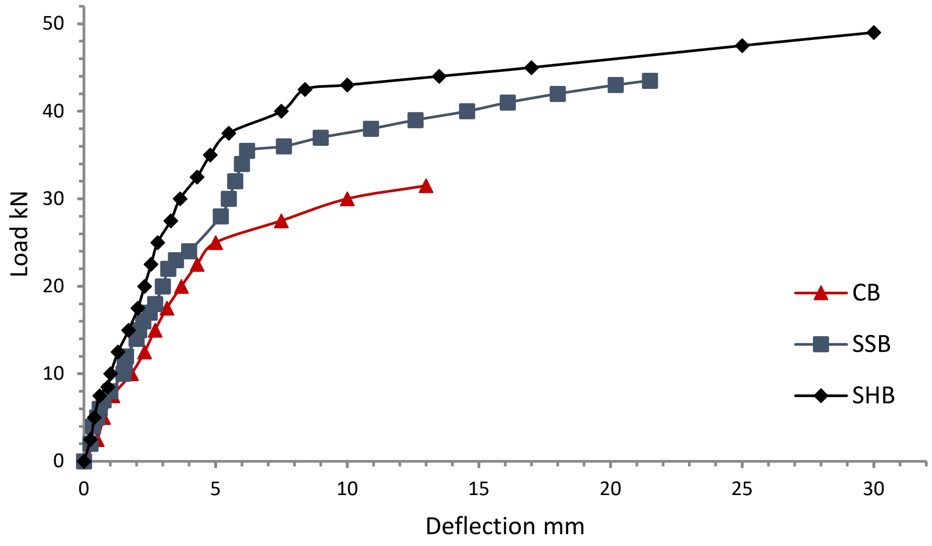

Fig.3. Load-Deflection Relationship of CB, SSB, and SHB

3.2 Load-concrete Compressive Strain

Fig. 4 represents load- compressive strain relationship of CB, SSB, and SHB. All beams showed a similar trend up to first cracking load; however, strain in CB is higher than other beams at the same load. After first cracking load, the strain in CB and SSB are nearly the same in some parts of working load, this behavior should not happen for SSB at this load level. This may be attributed to the cracks that may be occurring at the interfaces between the cement and aggregate near the strain gauges. It is considered from the comparison between SSB and SHB beams, that the compressive strains trend is nearly the same except the proceeding part for SHB beam up to ultimate load.

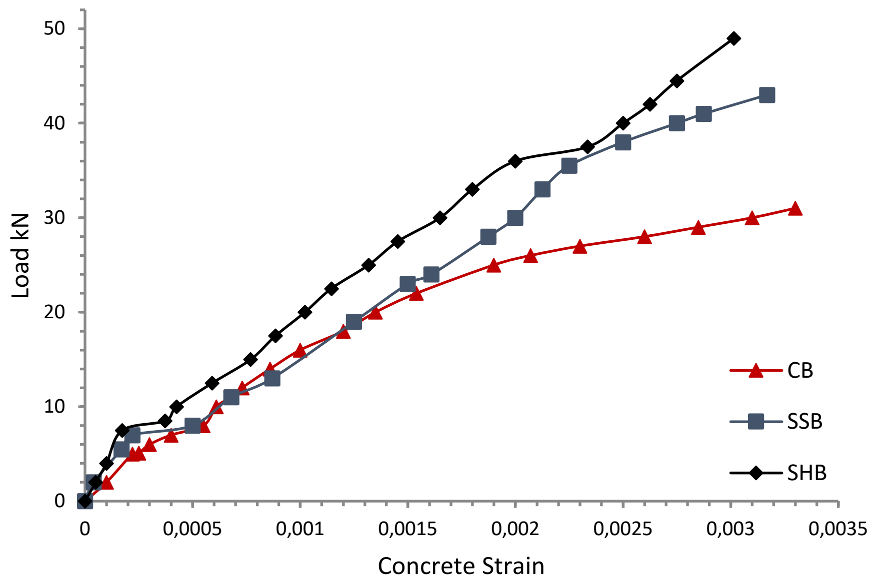

Fig. 4. Load-Strain in the Top Fiber of Concrete Relationship of CB, SSB, SHB

3.3 Failure Mode

At the beginning, all the beams showed a linear elastic behavior followed by appearance of several cracks in the mid-span region of the beams. A nonlinear behavior was recorded with the development of numerous flexural cracks and considerable deflections. By increasing the load, the stiffness of the beam changed dramatically with the yielding of the tensile steel reinforcements.

Beam CB failed in a conventional manner by concrete crushing at the compression zone after yielding of the tensile steel reinforcements.

As shown in Fig. 5, the failure mode of the strengthened beams began with yielding of the tensile steel reinforcements, followed by crushing of the concrete in the constant moment region, and finally cutting of the NSM bar. Parts of concrete crushed and separated from the tension part as shown in SHB2.

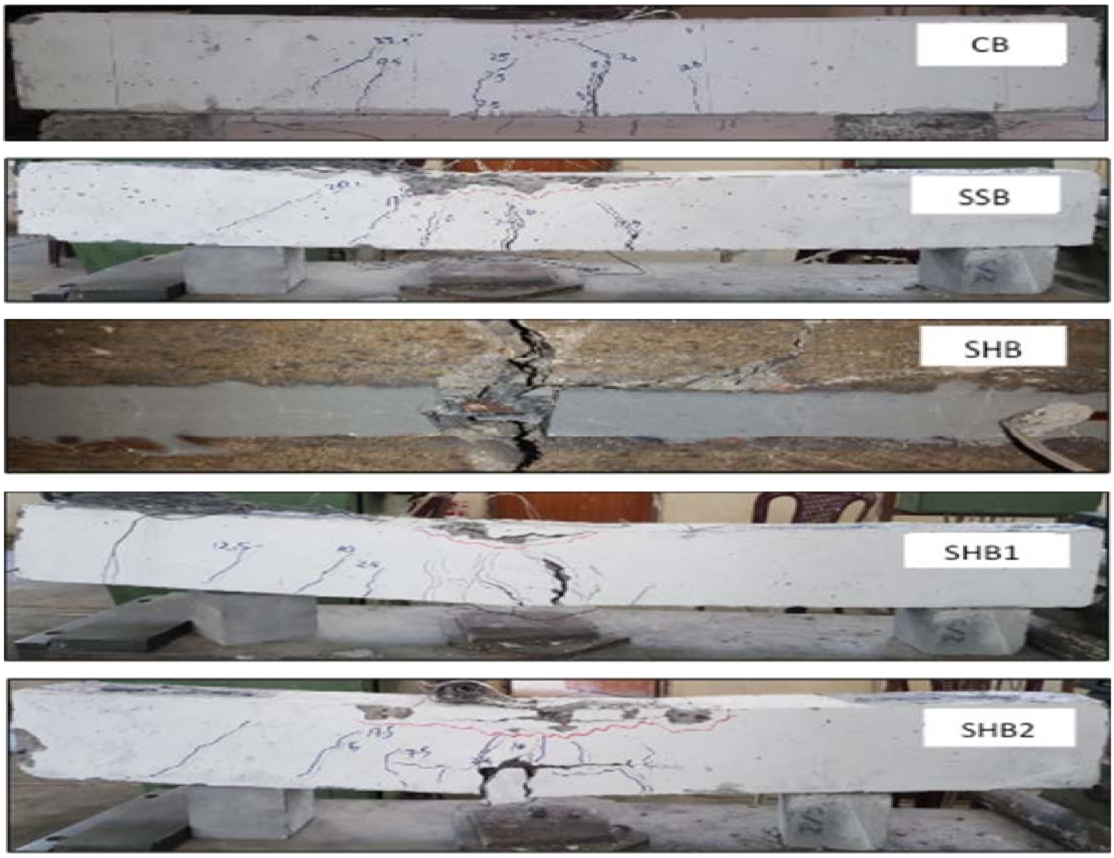

Fig. 5. Failure Mode of Tested Beams CB, SSB, SHB, SHB1, SHB2

3.4 Effect of Load Pattern

Fig. 6 shows the load versus the mid-span deflection of SHB, SHB1, and SHB2. It can be considered that the load pattern has an obvious effect on the beam behavior, so that the repeating load decreased the load capacity of the beams by about 65%, whereas the mid span deflection is nearly the same except for SHB1. The mid span deflection of SHB1 reduced about 19% as compared to SHB this was attributed to repeating load which was reduced the stiffness of the beam due to opening and closing cycle of the crack.
After the removal of the repeated load, the residual mid-span deflection will increase gradually till failure occurred as shown in fig. 6.

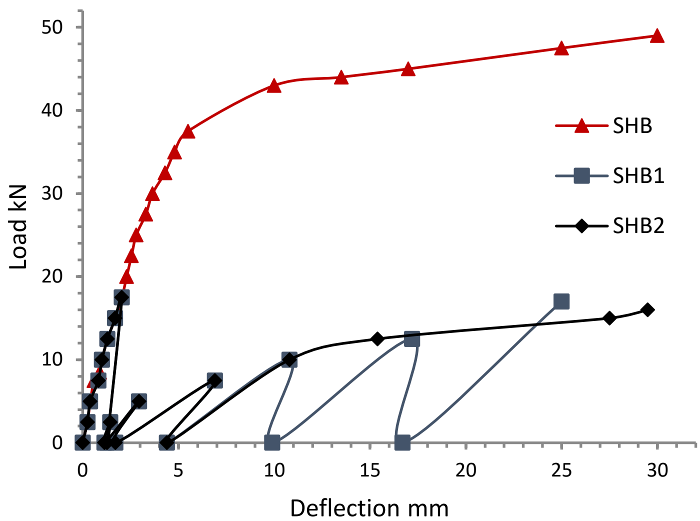

Fig. 6. Load-Deflection Relationship of SHB, SHB1, and SHB2

4 THEORETICAL WORK

A theoretical study has been conducted here on un-strengthened and strengthened RC beams based on a main assumption (a) a plane section remains plane before and after loading (b) The maximum compressive strain in the concrete is 0.003 with neglected tensile strength (c) the NSM hybrid steel bar has a behavior of a linear-elastic up to failure (d) perfect bond between NSM steel bar and the surrounding concrete has been assumed.

The load of the un-strengthened and strengthened RC beams is calculated at three stages, un-cracked, yield, and ultimate.

Fig. 7 represent the strain and the stress diagrams of the RC sections to be guidance for the calculation of the strain compatibility and force equilibrium equations.

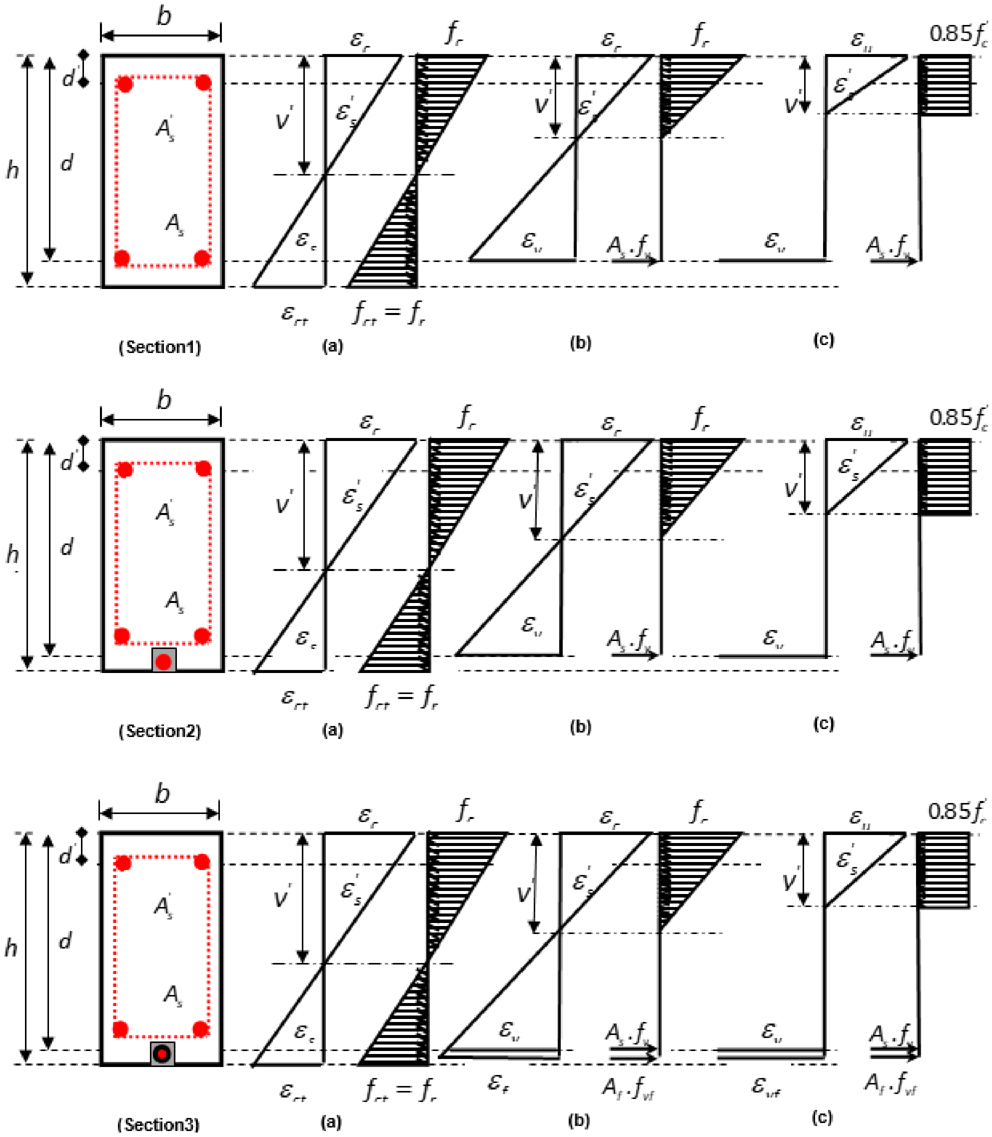

Fig. 7. The strain and stress diagrams for (Section1): un-strengthened section, (Section2): strengthened section with NSM steel bar, (Section3): strengthened section with NSM hybrid steel bar

(a): un-cracked stage, (b): yield stage, (c): ultimate stage

Notation:

A_s : is the area of tensile steel reinforcement.

A_s' : is the area of Compression steel reinforcement.

A_f : is the area of CFRP sheet.

f_{ct} : is the tensile stress in concrete.

f_c : is the compressive stress in concrete

f_{yf} : is the yield stress in CFRP sheet.

The modulus of rupture (f_r), the modulus of elasticity (E_c) for concrete, and the effective moment of inertia (I_e) of the section at each loading stage shall be calculated according to the ACI-318 (2019)[19]:

$$f_r = 0.62\lambda\sqrt{f_c^{'}} \quad (1)$$

$$E_c = \omega_c^{1.5} 0.043\sqrt{f_c^{'}} \quad (2)$$

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1-\left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \quad (3)$$

Where the modification factor (λ) shall be taken as 1.0 for normal weight concrete, the equilibrium density (ω_c) of the concrete mixture is between 1440 and 2560 kg/m^3, and the compressive strength of concrete ($f_c^{'}$) in MPa.

(M_{cr}): is the cracking moment.

(M_a): is the maximum moment in member due to service loads at stage load is calculated.

(I_{cr}): is the moment of inertia of cracked section transformed to concrete.

At strengthened beam with NSM steel bar, the strengthening bar concerned as tensile reinforcement. While in beam strengthened with NSM hybrid steel bar, the CFRP sheet concerned as an additional composite material with area (A_f) equal to 3.19 mm^2.

Table 3 summarized the theoretical analysis of the RC beams compared with experimental results.

Table 3. Theoretical and experimental results results

The Stage	Type of Beam	Tensile Reinforcement	Effective Depth d in mm	Theoretical Load in kN	Experimental Load in kN	The Difference %
Un-cracked Stage	CB	2Ø8	118	8.458	7.5	12.8
	SSB	3Ø8	126.67	9.03	7.5	20.4
	SHB	3Ø8+ A_f	126.67	9.08	7.5	21
Yield Stage	CB	2Ø8	118	22.61	25	-9.6
	SSB	3Ø8	126.67	35.7	32.15	11
	SHB	3Ø8+ A_f	126.67	36.88	33.25	10.9
Ultimate Stage	CB	2Ø8	118	29.09	31.5	-7.7
	SSB	3Ø8	126.67	45.22	40.48	11.7
	SHB	3Ø8+ A_f	126.67	46.21	42.75	8

5 CONCLUSIONS

The main conclusion of this investigation can be summarized as follows:

1. Strengthening of concrete beam with NSM steel bar increased the yielding and ultimate loads by about 28.6% and 28.5% respectively as compared to control beam.
2. Strengthening of concrete beam with NSM hybrid steel-CFRP bar increased the yielding and ultimate loads by about 33% and 35.7% respectively as compared to control beam.

3. The ductility index of CB equals to 2.6, whereas the ductility index of SSB and SHB increased to about 24.6% and 52.3% respectively over the ductility of CB.
4. It is considered from the comparison between SSB and SHB beams, that the compressive strains trend is nearly the same except the proceeding part for SHB beam up to ultimate load.
5. The repeating load decreased the load capacity of the strengthened hybrid beams by about 65%, whereas the mid span deflection is nearly the same.

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