Structural Engineering and Mechanics, *Vol. 70, No. 1 (2019) 67-80*
DOI: https://doi.org/10.12989/sem.2019.70.1.067

Behavior of RC beams strengthened with NSM CFRP strips under flexural repeated loading

Saja Waleed Fathuldeen[a] and Musab Aied Qissab*

Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq

(Received June 17, 2018, Revised February 7, 2019, Accepted February 8, 2019)

Abstract. Strengthening with near surface mounted carbon fibre reinforced polymers (NSM-CFRP) is a strengthening technique that have been used for several decades to increase the load carrying capacity of reinforced concrete members. In Iraq, many concrete buildings and bridges were subjected to a wide range of damage as a result of the last war and many other events. Accordingly, there is a progressive increase in the strengthening of concrete structures, bridges in particular, by using CFRP strengthening techniques. Near-surface mounted carbon fibre polymer has been recently proved as a powerful strengthening technique in which the CFRP strips are sufficiently protected against external environmental conditions especially the high-temperature rates in Iraq. However, this technique has not been examined yet under repeated loading conditions such as traffic loads on bridge girders. The main objective of this research was to investigate the effectiveness of NSM-CFRP strips in reinforced concrete beams under repeated loads. Different parameters such as the number of strips, groove size, and two types of bonding materials (epoxy resin and cement-based adhesive) were considered. Fifteen NSM-CFRP strengthened beams were tested under concentrated monotonic and repeated loadings. Three beams were non-strengthened as reference specimens while the remaining were strengthened with NSM-CFRP strips and divided into three groups. Each group comprises two beams tested under monotonic loads and used as control for those tested under repeated loads in the same group. The experimental results are discussed in terms of load-deflection behavior up to failure, ductility factor, cumulative energy absorption, number of cycles to failure, and the mode of failure. The test results proved that strengthening with NSM-CFRP strips increased both the flexural strength and stiffness of the tested beams. An increase in load carrying capacity was obtained in a range of (1.47 to 4.49) times that for the non-strengthened specimens. Also, the increase in total area of CFRPs showed a slight increase in flexural capacity of (1.02) times the value of the control strengthened one tested under repeated loading. Increasing the total area of CFRP strips resulted in a reduction in ductility factor reached to (0.71) while the cumulative energy absorption increased by (1.22) times the values of the strengthened reference specimens tested under repeated loading. Moreover, the replacement of epoxy resin with cement-based adhesive as a bonding material exhibited higher ductility than specimen with epoxy resin tested under monotonic and repeated loading.

Keywords: NSM CFRP; epoxy resin; cement based adhesive; flexural repeated loading; reinforced concrete beams; ductility factor

1. Introduction

Nowadays, strengthening of buildings' structural elements have been carried out widely worldwide. One of the ingenious strengthening techniques is the Near-Surface Mounted Carbon Fibre Reinforced Polymer (NSM-CFRP) which is a method by which carbon fibre reinforced polymers (CFRP) are placed in concrete cover at the tension side and bonded with a special materials such as (Epoxy and cement-based adhesive) (José *et al.* 2012). This method completely delays the deboning failure and improves the flexural capacity. Also, this method can be used without surface preparation and protect the fibre material from the external environmental conditions. FRP is important for civil engineering applications because it provides high tensile strength ($f_{fu} > 2400\text{MPa}$), high elastic modulus ($E_f > 160000$) and the material exhibit excellent fatigue resistance and low weight (Perumalsamy *et al.* 2008). NSM method appeared in Europe in (1950) for strengthening concrete structures. It was proved that NSM is more efficient, easy to fix, reduce the risk of installation and made a protection from environmental exposure. It was used for shear and flexural strengthening of concrete members(Nader 2009).The flexural behavior of concrete beams strengthened with externally bonded or NSM carbon fibre polymers was investigated by a number of researchers (Laura *et al.* 2000, Firas *et al.* 2009, Anders *et al.* 2001, Slavash and Al-Mahaidi 2008, Ibrahim *et al.* 2014, Ahmed 2014, Al-Abdwais and Al-Mahaidi 2016, Al-Abdwais and Al-Mahaidi 2017, Jiong-Feng *et al.* 2017, Mohammad *et al.* 2014, Dezhangah and Sepehrinia 2018) considering different parameters such as the type of bonding material and the CFRP geometry (bar, strip, textile).

Laura *et al.* (2000) investigated the effect of CFRP rods on the behavior of T-beams under four-point bending

*Corresponding author, Assistant Professor
E-mail: musabaq79@gmail.com
[a]M.Sc.
E-mail: sajanahren@mail.ru

ISSN: 1225-4568 (Print), 1598-6217 (Online)

monotonic and cyclic loadings. The authors reported that the strengthening with CFRP rods is more effective and significantly increase in load capacity range from 25% to 44.3% with respect to the reference beam. The authors noted that when the amount of CFRP increased the load capacity increased slightly. The behavior of RC beams strengthened with CFRP using two types of bonding materials was studied by Firas *et al.* (2009). The results showed that NSM is more effective method which significantly improves the strength capacity of the beams also it was noted that the use of epoxy resins resulted in excellent bond between concrete and CFRP rod compared to mortar due to the early deboning between concrete groove surface and mortar in a weak interfacial zone. Anders *et al.* (2001) investigated the behavior of RC beams strengthened with NSM fibre polymer using different types of bonding materials like epoxy and cement mortar. The beams were tested under four-point bending with displacement control. It was noted that when the load increases, the bonding mortar separated from grooves and deboned at 123.50kN while for the two beams bonded with resin the load capacity was 152.00 kN and 140.00 kN, respectively. The test results confirmed that specimens bonded with epoxy resin showed better performance (maximum load and deformation) compared to other specimens under monotonic loading. Nevertheless, when epoxy replaced by cement adhesive, the behavior could be substantially improved in site. Slavash and Al-Mahaidi (2008) the effect of using different types of cement mortar adhesive as bonding material in reinforced concrete beams strengthened with externally bonded carbon fibre sheets was examined. It was found that the capacity was increased from 60 to 200% with different mortars compared to non-strengthened control specimens. Ibrahim *et al.* (2014) carried out an experimental program to investigate the flexural strength and the effect of different variables such as types of resin, size and number of CFRP bars. The results showed that the effect of different epoxy types on the behavior of strengthened beams is omitted while the effect of increasing the number of CFRP bars from one to two increased the load carrying capacity by 7.50% over the beam strengthened with one bar. The principle failure modes of beams strengthened with one and two CFRP bars were interfacial deboning between epoxy-concrete and concrete cover separation (delamination), respectively. Ahmed (2014) studied two types of bonding materials (epoxy resin and cement-based adhesive) and two types of CFRP (laminate and textile). The results showed an increased in load carrying capacity of about 98% to 101% with respect to specimen with epoxy resin by using CFRP laminates and textile under monotonic loading while the mode of failure was interfacial debonding between bonding adhesive and fibre in specimen with cement-based adhesive and failed by concrete cover separation in specimen with epoxy adhesive. The fatigue behavior of eight reinforced concrete T-beams strengthened with carbon fibre strips was investigated by John *et al.* (2004). The load was applied with sinusoidal cycles at a frequency of 1 Hz under high stress range of approximately 80% of the yield load of reference specimen. It was found that fatigue life increased

Table 1 Details of experimental program

Group number	Specimens	Strengthening scheme					Loading type
		No. of grooves	Groove dimension (t*w) mm	Total no. of strips	Carbon fibre dimension (t*w) mm	Total area of CFRP (mm^2)	
(1)	BC1	---	---	---	---	---	Monotonic
	MG1B1	1	8*23	1	1.4*15	21.00	Monotonic
	G1B1						Repeated
	MG1B2	3	8*23	3	1.4*15	63.00	Monotonic
	G1B2						Repeated
(2)	BC2	---	---	---	---	---	Monotonic
	MG2B1	3	8*18	3	1.4*12	50.40	Monotonic
	G2B1						Repeated
	MG2B2	3	8*26	3	1.4*12	50.40	Monotonic
	G2B2						Repeated
(3)	BC3	---	---	---	---	---	Monotonic
	MG3B1	3	8*24	3	1.4*16	67.20	Monotonic
	G3B1						Repeated
	MG3B2	3	8*24	3	1.4*16	67.20	Monotonic
	G3B2						Repeated

with the increase amount of CFRP and the failure firstly occurred by bar rupture then cracks were extended along the mid span towards the supports which resulted in delamination of CFRP from concrete. Sungnam and Sun-Kyu (2016) carried out tests on four reinforced concrete beams strengthened with external bonded CFRP using one and two strips under cyclic loading. The specimens were tested under three-point load with a maximum load 60% of ultimate load of control beam at 2Hz frequency. The tests showed that the presence of CFRP strips in tension zone reduced the cracks' width and prevented its extension along the specimen unlike the non-strengthened specimens. Result also revealed that the energy dissipation was reduced by increasing the amount of CFRP strips. M Maalej and KS Leong (2005) examined synergistic combination of strengthening by external fibre bonded and engineered cementitious composite (ECC) as a bonding material for strengthening of two RC beams by CFRP sheet. The test results showed an improvement in the load carrying capacity and a reduction of the risk of CFRP layer deboning. Besides, a reduction in deflection when compared with control specimen. The ACI Committee 440 (2008) studied the flexural strengthening with near-surface mounted carbon fibre bars. The test variables were: reinforcement ratio and groove size. The test proved that the effect of FRP increase the load carrying capacity of the strengthened specimens. Also, results show ed that the decrease in groove size of FRP bar increase the distance between FRP and main reinforcement which as a result, delay the deboning failure. The critical failure mode was the concrete cover separation. Most previous researches have dealt only with strengthened beams under loads monotonically increased to failure. In practice, there are many cases that structures may be exposed to high intensity

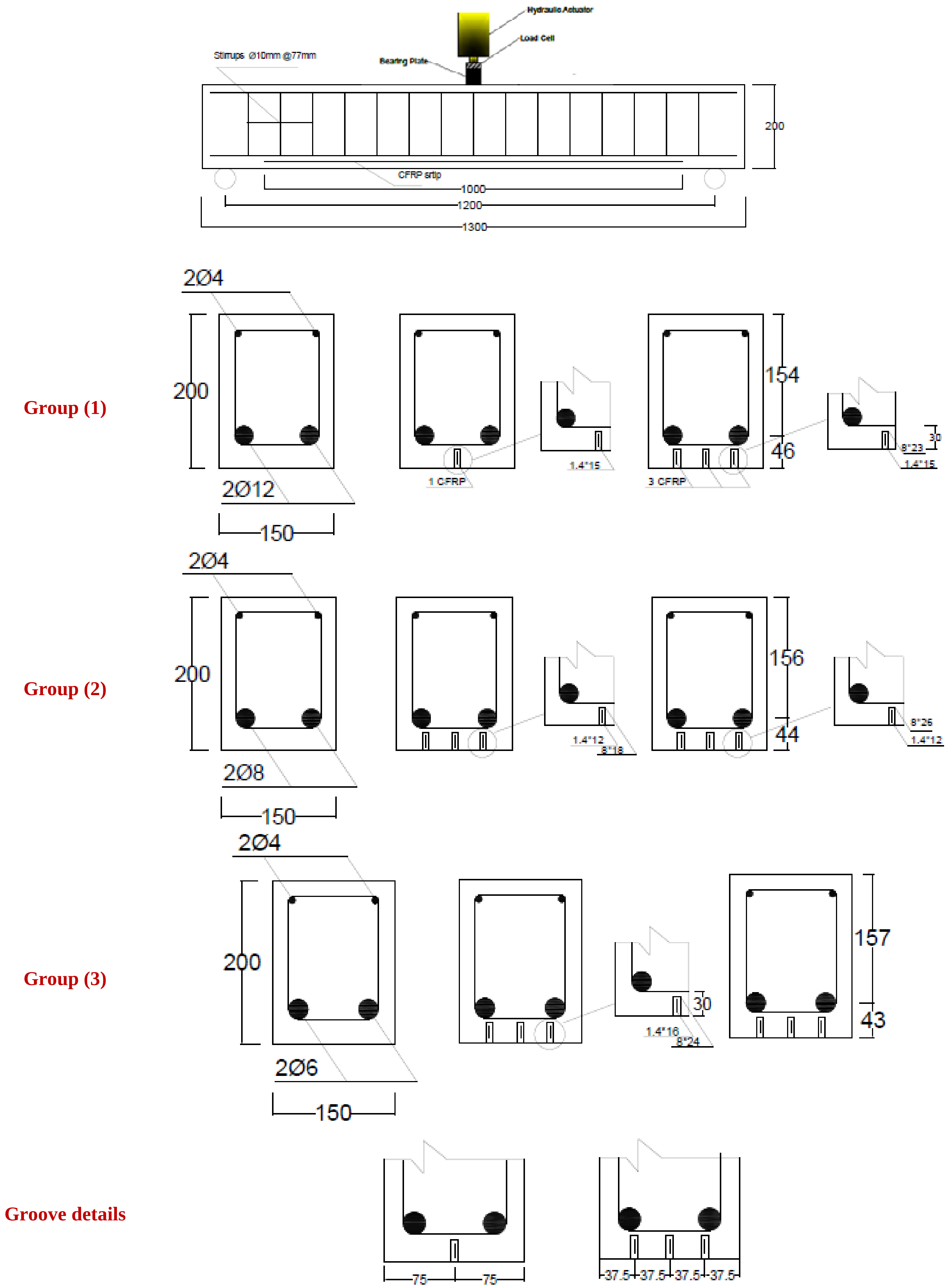


Fig. 1 Reinforcement details of test specimens

<u>All dimensions are in mm</u>

Fig. 2 CFRP installation steps: (a) cutting grooves, (b) grooves cleaned from dust and contaminations by compressed air, (c) CFRP installation, and (d) specimens after CFRP installation

Fig. 3 Specimens casting, curing, preparing for test

repeated load such as earthquakes or traffic load on bridges. As mentioned above, limited researches studied the behavior of NSM under repeated loading which conclude that the most failure mode may be happened either by concrete cover separation or interfacial debonding between adhesive-fibre or adhesive concrete by losing the composite action. More investigations are needed to study the effect of different bonding material, groove size, and number of CFRP strips on the flexural behavior of reinforced concrete beam strengthened with near surface carbon fibre reinforced polymers under repeated. The main aim of this research was to investigate the effect of these parameters under repeated load with special attention to:

- Load-deflection behavior at mid span
- Ultimate load carrying capacity
- Number of cycles to failure
- Ductility factor, cumulative energy absorption, and cracking pattern at failure

2. Experimental program

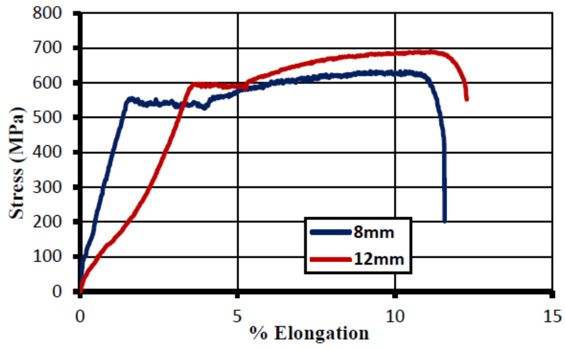


Fig. 4 Stress-Strain curves of (12 mm and 8 mm) diameter steel bars

2.1 Test program details

The experimental program of this study was designed to investigate different parameters including size of grooves, number of CFRP strips, type of bonding materials, and loading type. To achieve this goal, fifteen specimens were designed and prepared. The test specimens have dimensions of (150 mm width, 200 mm depth) and (1300 mm length). The specimens were divided into three groups and each group consists of five specimens four of them were strengthened and one non-strengthened as a reference one. The details and designation of test specimens are presented in Table 1. The test specimens were designed according to ACI 318-14 (2014) to fail in flexure and the shear failure was avoided by providing sufficient shear reinforcement. The tensile steel reinforcement ratio was $\rho_s = 0.98\%$, $\rho_s = 0.43\%$, and $\rho_s = 0.24\%$ for group (1), group (2) and group (3) respectively. The reinforcement details of test specimens are shown in Fig. 1. The surface of concrete was prepared before CFRP installation.

The Installation procedure recommended by the manufacturer is described in Fig. 2. Wooden molds were used for casting of specimens to obtain smooth surface. All molds have been treated with oil before inserting the reinforcement cage and plastic spacers have been used to provide a 30 mm cover. After 24 hour of casting, specimens have been removed out of the molds and the specimens were covered with burlap sacks which were kept wet for fully 28 days as shown in Fig. 3.

2.3 Strengthening of test specimens

Twelve out of fifteen test specimens were strengthened with carbon fibre strips ($CFRP_s$). The surface of concrete was smoothed before CFRP installation. After 28 days of curing, grooves with ($3a_b, a_b$: is the thickness of the strip) width and ($1.5\ b_b, b_b$: is the width of the strip) depth according to ACI 440.3R-08 (2008) (the details of groove size for each group are described in Table 1 and shown in Fig. 1) were cut in concrete cover by using diamond cutter then the grooves were cleaned by compressed air to remove the dust and gain better bond. CFRP was cut to 1000 mm in length strips and cleaned from dust, oil, grease and other contamination before installation. Grooves were filled with epoxy adhesive then carbon fibre had been inserted into the

Table 2 Mix proportion of concrete and cement-based adhesive

Mixture type	OPC (type I) (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (L/m^3)	W/C (%)	Silica fume (kg/m^3)	Super-plasticizer 5930(L)	SBR (L)
Concrete	420.00	700.00	1100.00	189.00	0.45	-	-	-
Cement-based adhesive	910.00	960.00	-	349.44	0.32	182.00	8.74	54.60

Table 3 Test results of compressive strength, splitting tensile strength, and flexural strength of test specimens

Specimens designation	Compressive strength (MPa) for cylinder	Compressive strength (MPa) for cube	Splitting tensile strength results (MPa)	Flexural strength (MPa)	Modulus of elasticity (E_c, MPa)
BC1, BC2, BC3	32.24	36.30	3.28	3.69	26686.73
MG1B1, 1B1	31.20	38.69	3.34	3.37	26252.77
MG1B2, G1B2	31.35	40.91	3.30	3.54	26315.80
MG2B2, 2B2	30.98	37.64	3.18	3.86	26160.05
MG3B1, 3B1	32.67	40.52	2.98	3.98	26864.11

Table 4 Tensile test results of reinforcement bar

Diameter of bar (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation %
12	592.40	689.90	12.30
10	622.60	714.40	11.30
8	550.00	633.30	10.80
6	540.37	600.05	6.67
4	780.28	832.56	2.12

Table 5 Mechanical Properties of CFRP, epoxy resin, and Cement-based adhesive

Materials	Tensile strength (MPa)	E-modulus (MPa)	Strain at break (%)	Compressive strength (MPa)
Carbon fibre	2400.00	165000.00	1.20	---
Epoxy resin	26-31	9600.00	---	85-95
Cement-based adhesive	6.30	24000	---	60.03

grooves and the excess adhesive had been removed from the surface. Adhesive was allowed (7 days) for curing in air, before tests all specimens. The procedure of strengthening specimens is shown in Fig. 2.

2.2 Material properties

The concrete mix was designed according to British Mix Design Method BS 5328 part 2:1997. The target compressive strength was (33 MPa) with a slump of (10 mm). The mix proportions used in this study are given in Table 2. The compressive strength was determined according to BS1881: part 116:1989 and the ASTM C39/C39M-03(2005) specifications. For each beam, the average value for three cubes with (150*150*150) mm dimensions and the average value for three cylinders with (150 mm diameter, 300 mm height) at 28 days were used as the compressive strength of concrete. The splitting tensile strength value was obtained according to ASTM C496/C496M-11 (2011) by averaging three test values, at an age of 28 days of curing while flexural strength was obtained according to ASTM C78 -10 (2002). The results of

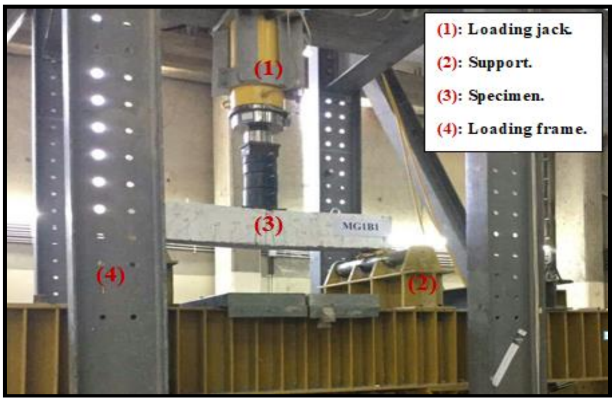


Fig. 5 Specimen test setup

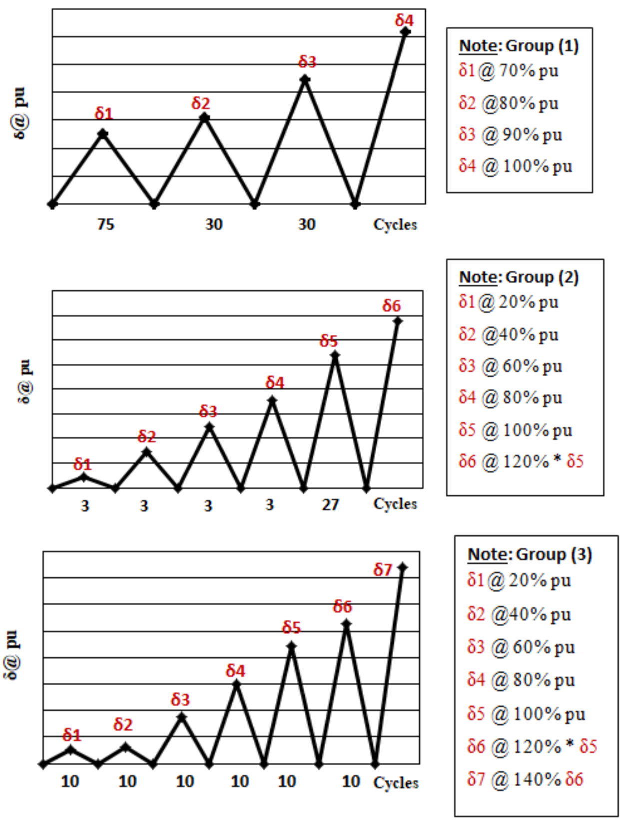
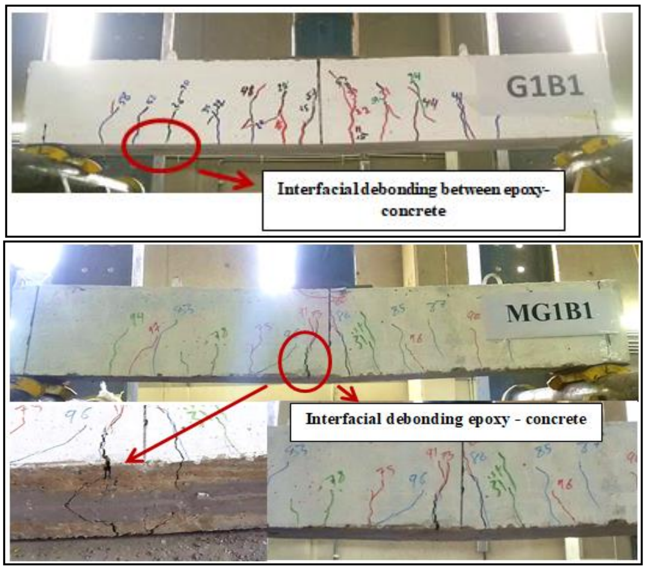


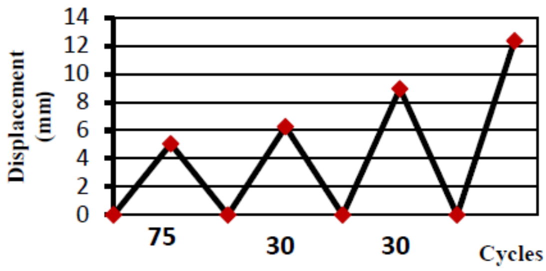
Fig. 6 Displacement history for specimens of group (1), (2), and (3)

the compressive strength, splitting tensile strength and flexural strength of test specimens are presented in Table 3. Deformed bar with (12, 10, 8) mm diameter and deformed steel wires with (6, 4) mm were used in this study. Tensile test was carried out for each bar type and the results are presented in Table 4. The stress-strain curves of 8 mm and 12 mm bar diameter are shown in Fig. 4.

Carbon fibre (XS514) type was used in this study for flexural strengthening. Two types of adhesives were used; epoxy Sikadur30Lp and cement-based adhesive as an alternative bonding material between carbon fibre and concrete. The major components of cement-based adhesive are OPC type I, fine sand with gradation range 0.08-0.2, silica fume, super-plasticizer 5930, and SBR (Styrene

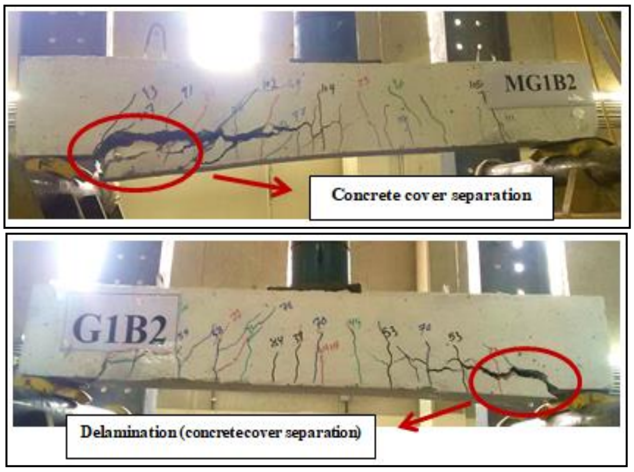


(a)

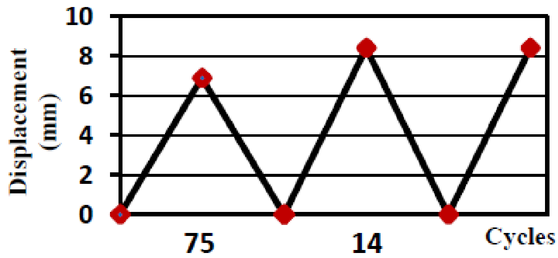


(b)

Fig. 7(a) Cracking pattern of test specimen of group (1), (b) Displacement history of test specimens of group one



(a)



(b)

Fig. 7 Continued

butadiene copolymer latex). The mix proportions of cement-based adhesive designed in this study are illustrated in Table 2. The compressive strength test of cement-based adhesive for three cubes (50*50*50) mm was carried out according to ASTM C109-02 (2002) and splitting tensile strength test for three cylinders (100*200) mm was carried out according to ASTM C496/C496M-11 (2011). The Mechanical and physical properties of the epoxy resin, cement-based adhesive, and carbon fibre reinforced polymer strips are presented in Table 5.

2.4 Test setup

All specimens have been tested by a universal testing machine with a maximum load capacity of (2000 kN). The machine was provided by an actuator and data logger acquisition system which recorded the load and deflection at every second and saved the results in a form of excel sheet. The specimens were simply supported over a span length of (1200 mm) and each specimen was tested under a monotonic or repeated concentrated load at mid span as shown in Fig. 5. A displacement control method was used to apply the vertical repeated load at the top of the specimen. For all specimens, the loading cycles were applied until failure and the load-deflection behavior, mode of failure, energy absorption capacity, displacement ductility factor, and the effect of loading type were all monitored and investigated. The displacement history used for each group is shown in Fig. 6. Designations of test specimens are described as follows:

BC1 (B: Beam, **C**: Control without strengthening, **1**: Group (1))

MG1B1 (**M**: Monotonic loading, **G1**: Group number, **B1**: Strengthened beam number)

G1B1 (**G1**: Group number, **B1**: Strengthened beam number under repeated loading)

3. Test results of specimens in group (1)

The specimens in this group were designed to investigate the effect of the number of NSM-CFRP strips on the flexural behavior of reinforced concrete beams. This group consists of five beams, four beams strengthened with CFRP strips. Two of the strengthened beams were tested under monotonic loading to obtain the ultimate capacity while the other two specimens were tested under repeated loading. The fifth beam was non-strengthening as a reference one and tested under monotonic loading. The details of strengthening scheme are mentioned in Table 1. The displacement history used in this group is shown in Fig. 6.

2.5 Load deflection behavior, number of cycles, and mode of failure

Specimens in group (1) have a tensile steel

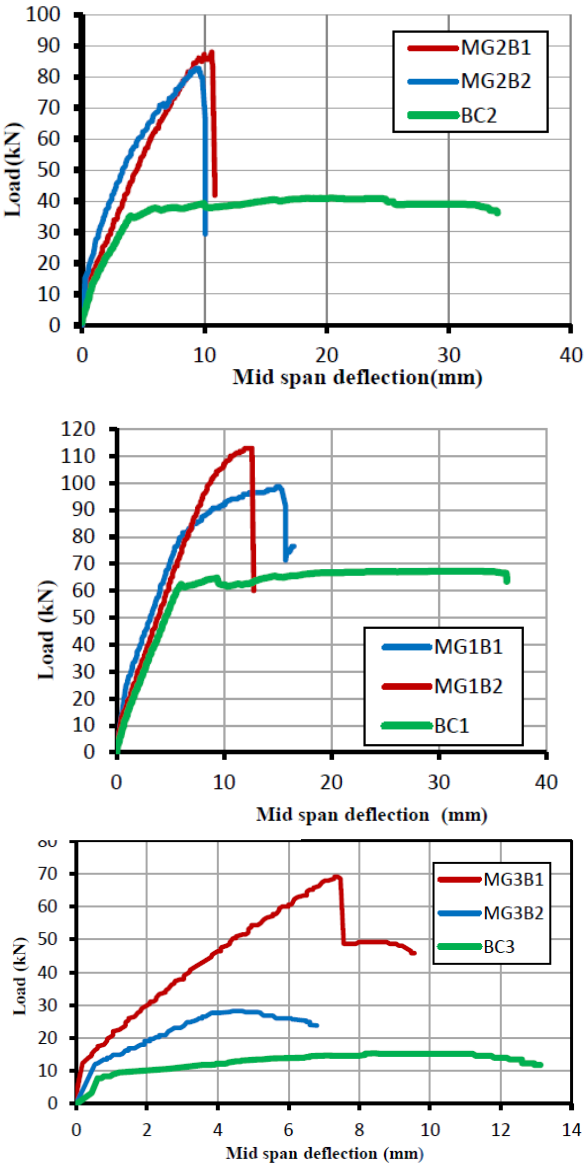


Fig. 8 Load-deflection curves of test specimens under monotonic loading

reinforcement ratio of (1.2%). Specimen (BC1) was used as a reference non-strengthened specimen which was tested under monotonic loading until failure. The beam failed at a load of (67.3 kN) with a corresponding deflection of (34.1 mm). The dominating failure mode was concrete crushing after steel yielding as shown in Fig. 7.

Specimens MG1B1 and MG1B2 were strengthened with one and three CFRP strips with dimensions of (1.4 mm thickness, 15 mm width) respectively. The specimens failed at a load of 98.60 kN and 112.8 kN respectively under monotonic loading. The ultimate load for MG1B1 and MG1B2 was (1.47) and (1.68) times that for the non-strengthened beam (BC1) which confirms that the strengthened specimen exhibited a higher strength. The deflection was reduced to (0.45) and (0.37) times that for (BC1) non-strengthened specimen because the CFRPs restrict the cracks extension and widening at the tension face and led to a brittle failure. For specimen MG1B1, the

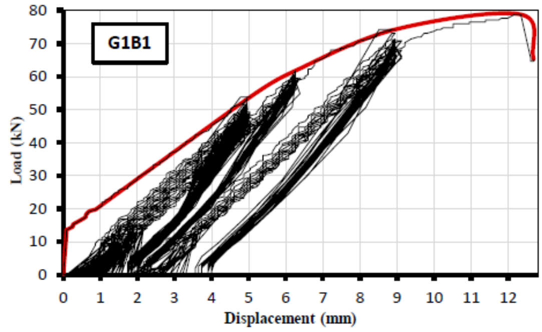
Table 6 Results of test specimens

Group No.	Specimen Designation	Maximum load (kN)	Deflection at Maximum load(mm)	Number of cycles to failure	Loading type	Mode of failure
	BC1	67.30	34.10	---	Monotonic	C
	MG1B1	98.60	15.20	---	Monotonic	FC
(1)	MG1B2	112.80	12.60	---	Monotonic	DB
	G1B1	78.80	12.30	136	Repeated	FC
	G1B2	103.18	8.90	90	Repeated	DB
	BC2	40.99	15.38	---	Monotonic	C
	MG2B1	88.00	10.60	---	Monotonic	DB
(2)	MG2B2	82.70	9.60	---	Monotonic	DB
	G2B1	68.50	13.00	40	Repeated	FC
	G2B2	58.90	9.90	36	Repeated	DB
	BC3	15.38	8.43	---	Monotonic	SY
	MG3B1	69.00	7.38	---	Monotonic	SH
(3)	MG3B2	28.00	4.69	---	Monotonic	FC
	G3B1	66.28	9.10	51	Repeated	SH
	G3B2	25.80	6.30	61	Repeated	FC +PRs

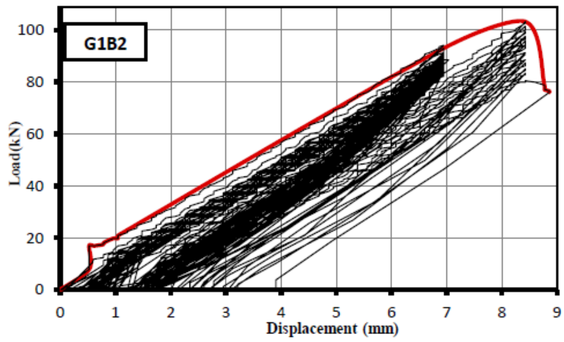
Note: SH: shear failure induced debonding; SY: steel yielding; C: concrete crushing; FC: flexure crack induced debonding failure; DB: end debonding failure; PRs: partial rupture of CFRP strip

failure occurred due to deboning between epoxy-concrete interfaces followed by concrete crushing in compression zone as shown in Fig. 7. Failure of MG1B1 formed by a flexural crack appeared at the maximum moment region which extended to the bottom of beam with an inclined angle with respect to horizontal axis while specimen MG1B2 failed by concrete cover delamination failure. The delamination started by a crack near or at the end of strips as a result of high interfacial shear and normal stresses. Furthermore, the ultimate deflection and ultimate load of MG1B2 were (0.83) and (1.14) times specimen MG1B1 respectively. It was also found that when the number of CFRP strips increased, the ultimate strength increased slightly because the ultimate capacity of beams was governed by the delamination of the concrete cover. The load-deflection behavior for specimens of group (1) under monotonic loading are shown in Fig. 8.

Specimens G1B1 and G1B2 were similar to specimens MG1B1 and MG1B2 but they were tested under repeated loading. Specimen G1B1 failed during the cycle number (136) at a load of (78.8 kN) with a corresponding deflection of (12.3 mm) while specimen G1B2 failed at cycle number (90) at a load of (103.181 kN) with a corresponding deflection of (8.4 mm). It can be seen from the recorded results in Fig. 9 for these specimens that the failure load of specimen G1B2 was (1.309) times that for specimen G1B1 which confirms that the increase of number of CFRPs from one (21 mm^2) to three (63 mm^2) increased the peak load of strengthened specimen under repeated loading. Also, the deflection at failure for specimen G1B2 was (0.72) times



(a)



(b)

Fig. 9 Load-deflection curve of test specimens under repeated loading: (a) specimen G1B1; (b) specimen G1B2

Table 7 Results of cumulative absorption energy and displacement ductility of test specimens

Group No	Specimen designation	Displacement ductility factor	Cumulative energy absorption (kN.mm)
	BC1	6.15	2197.70
	MG1B1	2.59	1238.00
(1)	MG1B2	1.33	902.80
	G1B1	1.53	20105.00
	G1B2	1.09	24519.16
	BC2	8.75	12055.02
	MG2B1	1.24	591.20
(2)	MG2B2	1.22	587.50
	G2B1	1.30	6576.80
	G2B2	1.29	5875.5
	BC3	1.95	166.97
	MG3B1	1.08	321.00
(3)	MG3B2	1.74	130.49
	G3B1	1.02	5206.00
	G3B2	1.53	1005.98

that for specimen G1B1 as a result of increasing stiffness. Specimen G1B1 failed by deboning between epoxy and concrete followed by concrete crushing. Specimen G1B2 failed by cover separation at the cutoff point of the CFRP as shown in Fig. 7 due to the high concentration of shear stresses at both ends of the CFRP strips as well as at the vicinity of flexural cracks. The test results are presented in Table 6.

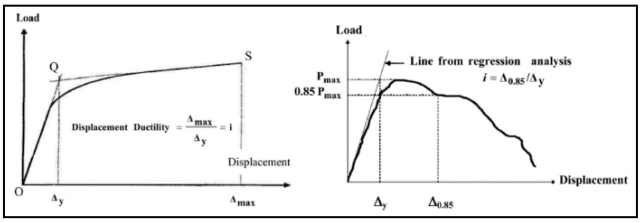


Fig. 10 Definition of displacement ductility (Mehrollah *et al.* 2014)

The load-deflection and envelope curves for test specimens of group (1) under repeated loading are shown in Fig. 9.

3.1 Displacement ductility factor and cumulative energy absorption

In this section, the displacement ductility factor and cumulative energy absorption are presented and discussed. Flexural ductility factor is an important property because a ductile structure provides a large deformation capacity without losing its strength and provides previous warning before failure. The ductility factor of can be defined as the ratio of ultimate displacement to the yield displacement while the cumulative energy absorption is defined as the area under load-deflection curve.

The displacement ductility and energy absorption of test specimens are presented Table 7.

It can be concluded that when the number of CFRP strips increased in specimen G1B2, the specimens' behavior was translated from ductile to brittle and on the other hand, these strips restricted the cracks widening or opening. It can be seen from the presented results for these specimens that there was a reduction in the displacement ductility factor by (29%) compared to G1B1 in addition to the decrease of the number of cycles to failure from 136 to 90. Also, the absorbed energy was increased by 1.22 times specimen G1B1. Fig. 10 shows the ductility factor definition and calculation method used in this paper while Fig. 11 shows the ductility parameters of test specimen. Figs. 12 and 13(a) show the displacement ductility and cumulative absorption energy of group (1).

4. Test results of specimens in group (2)

In this group, four beams with a tensile steel ratio of (0.58%), two of them were strengthened with NSM-CFRP strips and tested under monotonic loading while the other two specimens were tested under repeated loading. The fifth specimen was non-strengthened as a reference specimen and tested under monotonic load. The specimens in this group were designed to study the effect of groove size (two different groove depths were considered in this study: a depth of 18 mm was used as a reference value which was selected according to ACI440.3R-08 (2008) and a depth of 26 mm. The displacement history used for group (2) is shown in Fig. 14.

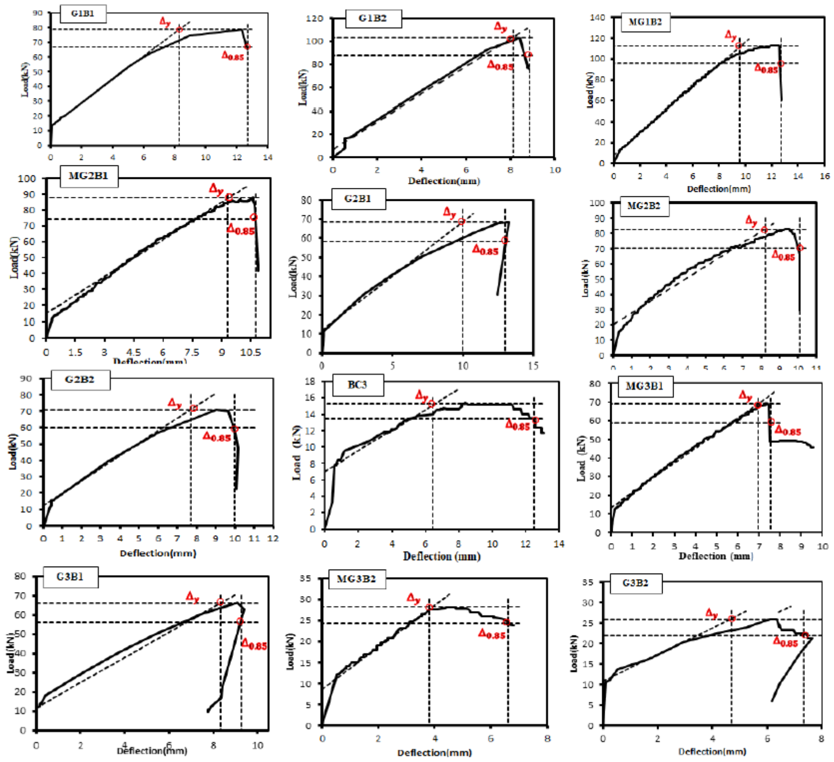


Fig. 11 Displacement ductility parameters of test specimens

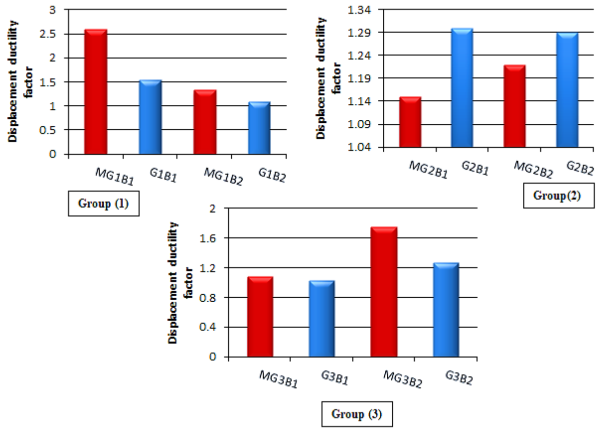


Fig. 12 Displacement ductility factor of strengthening specimens in group (1), (2), and (3)

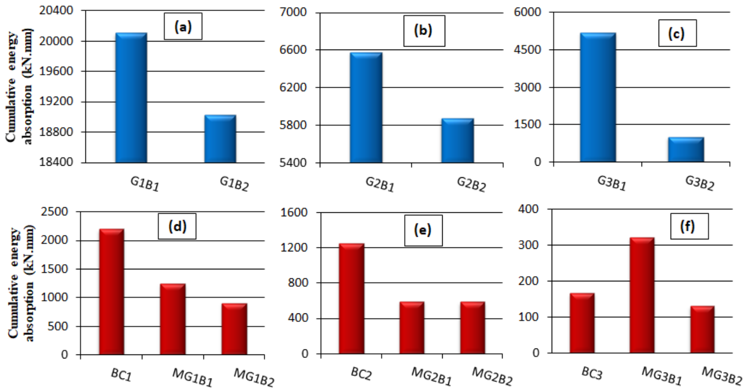
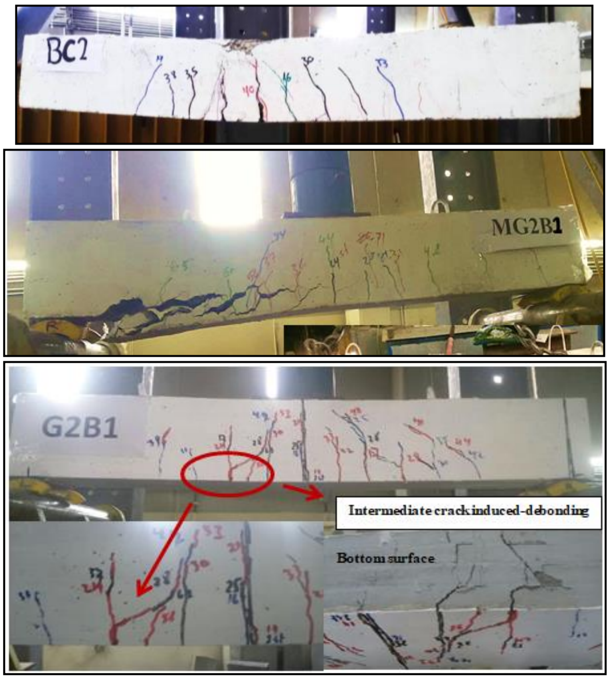
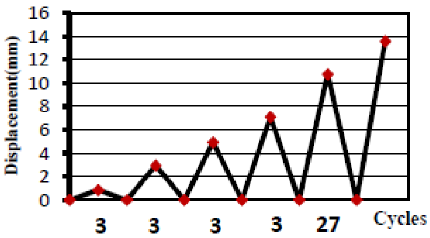


Fig. 13 Cumulative energy absorption of test specimens: (a) specimens in group (1) under repeated load, (b) specimens in group (2) under repeated load, (c) specimens in group (3) under repeated load, (d) specimens in group (1) under monotonic load, (e) specimens in group (2) under monotonic load, (f) specimens in group (3) under monotonic load



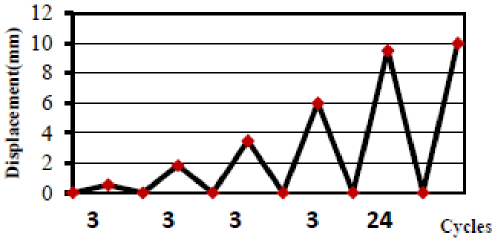
(a)



(b)

Fig. 14(a) Cracking pattern of test specimen in group (2), (b) Displacement history of test specimens of group (2)

(a)



(b)

Fig. 14 Continued

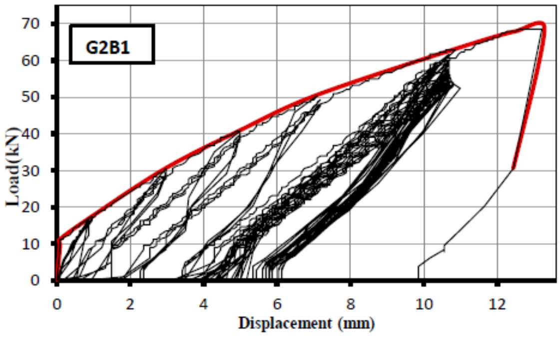


Fig. 15 Load-deflection response of G2B1 under repeated loading

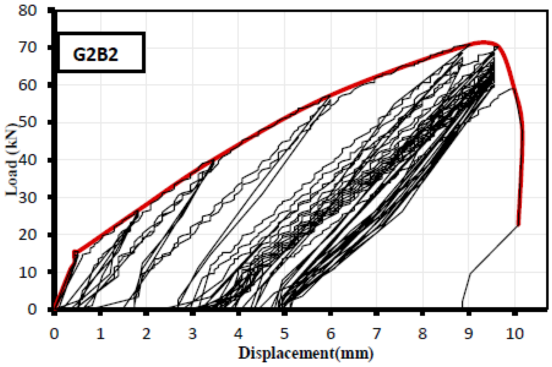


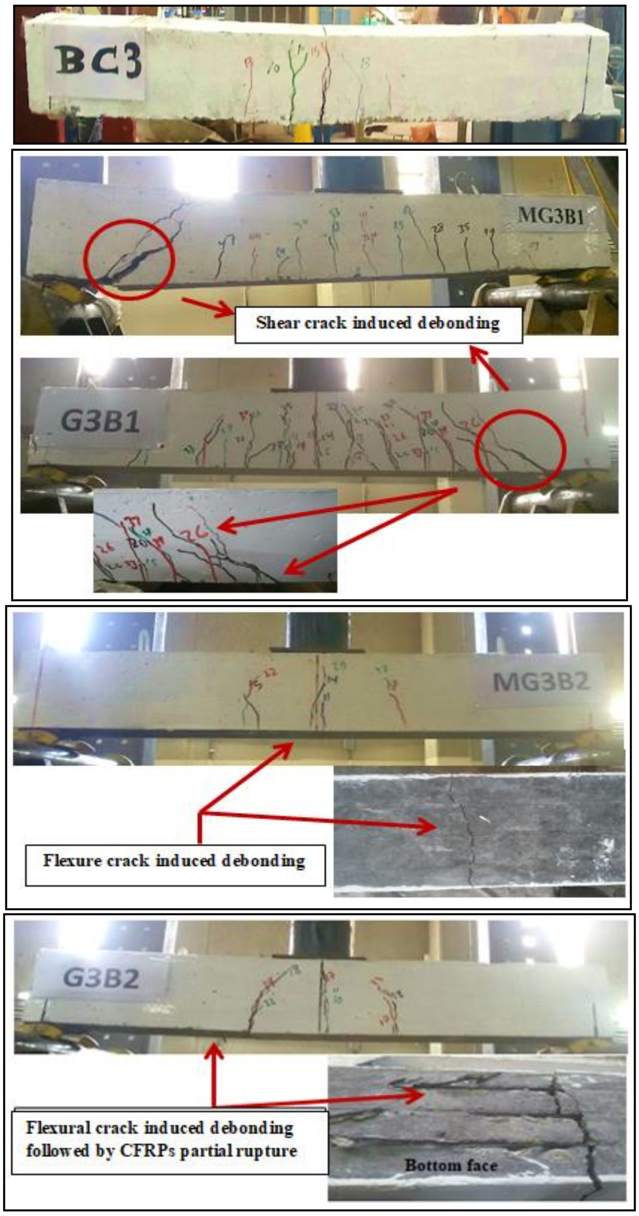
Fig. 16 Load-deflection response of G2B2 under repeated loading
0

4.1 Load deflection behavior, number of cycles, and mode of failure

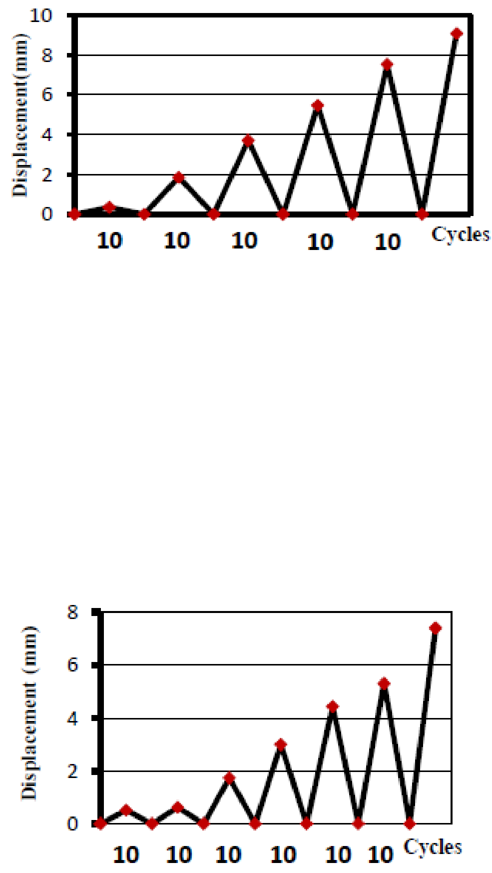
Specimen BC2 was used as a reference non-strengthened one. The maximum deflection obtained was (15.80 mm) with a failure load of (40.99 kN). The principle failure mode was steel yielding followed by concrete crushing.

Beam MG2B1 was strengthened with three NSM-CFRP strips with a total area of (50.4 mm^2) .The groove depth used for this specimen was (18 mm) which is equal to (1.5 b_b width of strip) according to ACI440.3R-08(2008). Beam MG2B2 was strengthened with three NSM-CFRP strips with a total area of (50.4 mm^2). The groove depth used for this specimen was (26 mm) which is equal to (2.2 b_b, b_b: width of strip). The ultimate load obtained (88.0 kN and 82.7 kN) with a corresponding deflection of (10.6 and 9.6 mm) for specimens MG2B1 and MG2B2 respectively. From the test results, it was found that the maximum load and deflection were decrease by about (6% and 9%) compared to specimen MG2B1. Also, it can be seen from the presented results in table 6 that the load carrying capacity of specimens MG2B1 and MG2B2 was (2.15) and (2.02) times that for the non-strengthened specimen BC2 which confirms the effectiveness of the strengthening technique. The load-deflection curves of MG2B1 and MG2B2 are shown in Figs. 16 and 17 respectively.

Specimens G2B1 and G2B2 were similar to specimens MG2B1 and MG2B2 but they were tested under repeated



(a)



(b)

Fig. 17(a) Cracking pattern of test specimens in group (3), (b) Displacement history of test specimen of group (3)

loading. Beam G2B1 failed at cycle number (40) with a maximum load was (68.50 kN) and a corresponding deflection of (13.00 mm) while the beam G2B2 failed at cycle number (36) with a maximum load of (69.12 kN) and the corresponding deflection was (9.56 mm). When the depth of groove increased from (18 mm) in beam G2B1 to (26 mm) in beam G2B2, the ultimate load approximately unchanged and the deflection was reduced by (26.46%) compared to G2B1. The principle failure mode for specimens MG2B2 and G2B2 was concrete cover separation or premature debonding failure. Specimen MG2B1 failed by the end interfacial debonding (or premature debonding failure) started at cut off points of CFRP strips and extended toward the center of span as shown in Fig. 14. This type of failure happened due to the high interfacial stresses near the end of the strips, and as a result, the NSM-CFRP strips separated from concrete while in beam G2B1 the dominant failure mode was interfacial deboning between concrete and epoxy at the bottom face of the beam as a result of flexural cracks propagated toward the bottom face of the beam. The results proved that there is insignificant effect of increasing the depth of grooves on the ultimate load of RC beams strengthened with CFRP under monotonic and repeated loading**.** The ultimate deflection was affected more by this increment. The load-deflection and envelope curves under repeated loading are shown in Figs. 15 and 16.

4.2 Displacement ductility factor and cumulative energy absorption

From the recorded results of group (2) in Table 7, it can be seen that there was a slight decrease in the ductility factor and cumulative energy absorption when the groove size increased from ($1.5b_b$) to ($2.2b_b$). Also, specimens under repeated loading showed a more ductile behavior compared with the strengthened counterpart under monotonic loading because of the damage accumulation from each cycle and distribution cracks along the span of beam under repeated loading case. Figs. 12 and 13 show the displacement ductility factor and absorbed energy for specimens in this group.

4.3 Test results of specimens in group (3)

Specimens in this group have a tensile reinforcement ratio of (0.44%), four of them were strengthened with CFRP strips and the remaining specimen was non-strengthened as a reference one. The specimens in this group were designed to investigate the effect of different bonding materials on the flexural behavior of reinforced concrete beams. Two types of adhesives were used; epoxy resin and cement based adhesive. Two of the test specimens were used as reference strengthened beams and tested under monotonic loading while the remaining specimens were tested under repeated loading. The details of strengthening scheme are explained in Table 1. The displacement history used for group (3) is shown in Fig. 6. The test results are presented and discussed in the following sections.

4.4 Load deflection behavior, number of cycles, and mode of failure

Specimen BC3 was used as a control non-strengthened specimen and tested under monotonic loading until failure. From Table 6, the failure load obtained was (15.38 kN) with a deflection of (8.45 mm). As the load increased, the cracks appeared at mid span and spread toward the top of the beam. The principle failure mode was traditional flexural failure due to formation of plastic hinge at mid span as shown in Fig. 17. Specimens MG3B1 and MG3B2 were strengthened with three NSM-CFRPs bonded with epoxy resin and cement-based adhesive respectively with an area of ($67.2\ mm^2$). The grooves size used was (24 mm) according to ACI440.3R-08(2008). Specimens MG3B1 failed by the combination of two mechanisms. The first mechanism cause by initial debonding started at the end of strip. The second one caused by the vertical movement of inclined crack toward the top of beam. This mode of failure called shear crack-induced debonding. As shown in Fig. 15, for specimen G3B1 and at a load of (69 kN), the inclined crack was appeared at a distance (165 mm) from the center of support and raised to a height of (90 mm) measured from the bottom face of beam. The specimen failed at a corresponding deflection of (7.38 mm). The use of CFRP strips increased the failure load by (4.49) while the deflection was (0.88) times the reference non-strengthened specimen BC3 values. Specimen MG3B2 failed at a load of (28.24 kN) with a corresponding deflection of (4.69 mm). The ultimate load was increased by (1.82) and the deflection was (0.56) times that for reference specimen BC3 values. The obtained results confirm the improvement of load carrying capacity for beam MG3B2 with respect to non-strengthened beam BC3. This indicates that the bonding material improved the composite action between

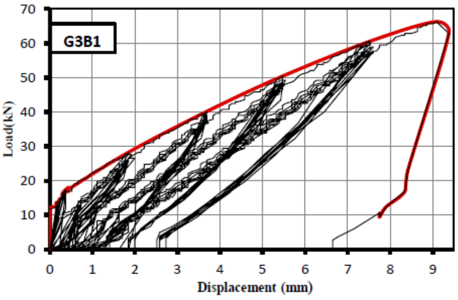


Fig. 18 Load-deflection response of G3B1 under repeated loading

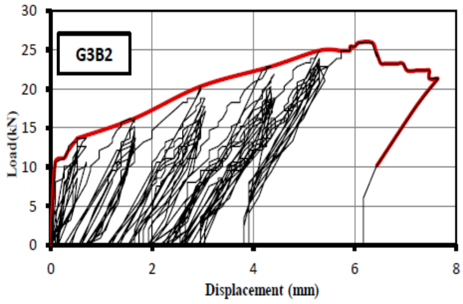


Fig. 19 Load-deflection response of G3B2 under repeated loading

CFRP and concrete, i.e., the stress was transferred effectively from concrete to fibre. It was also observed that specimen MG3B2 behaved brittle in comparison to the control beam.

When epoxy resin was replaced by cement-based adhesive, the strength of the beam MG3B2 with cement-based adhesive reduced to (0.41) and the deflection was reduced to (0.64) times the values of specimen MG3B1 with epoxy resin. This is due to the fact that epoxy adhesive has high mechanical properties and more compatible with NSM-CFRP strips compared with the cement mortar. This attributed to the early debonding failure between fibre and cement based adhesive at mid span and the load carrying capacity was not developed as for the beam bonded with epoxy. These results agreed with the findings obtained by previous researchers **(**Anders *et al.* 2001) and (Firas *et al.* 2009). The load-deflection curves for specimens in this group tested under monotonic loading are shown in Fig. 8.

Specimens G3B1 and G3B2 are designed similar to MG3B1 and MG3B2 respectively and tested under repeated load. Beam G3B1 failed at a load of (66.28 kN) in cycle number 51 with a corresponding deflection of (9.10 mm). The crack propagated and inclined toward the top of the beam. The mode of failure was transferred from flexure to shear failure due to the effect of NSM-CFRP strengthening as explained previously while specimen G3B2 failed at cycle number 61 with a maximum load of (25.80 kN) and a corresponding deflection of (6.30 mm). The cracks appeared and developed at midspan of the beam. These cracks were widened and propagated gradually during each cycle and turned towards the end of the strips at the cutoff point causing debonding of mortar and concrete followed by partial rupture of the CFRP strips. It was found that the strength of specimen with cement- based adhesive was decreased to (0.39) times the value of specimen G3B1 with epoxy resin whereas the deflection was reduced to (0.69) times the G3B1 value. Despite of the reduction in ultimate deflection in specimen G3B2, a higher number of cycles to failure and a ductile behavior was observed. The load-deflection and envelop curves are shown in Figs. 18 and 19.

4.5 Displacement ductility factor and cumulative energy absorption

It can be seen from Table 7 that specimens MG3B1 and MG3B2 have a reduction in displacement ductility factor with respect to specimen BC3. The cumulative energy absorption was reduced in specimen MG3B2 to (0.78) and increased in specimen MG3B1 to (1.92) times that for specimen BC3. Furthermore, it was shown that the cumulative energy absorption of MG3B2 was reduced to (0.41) while the displacement ductility factor was increased to (1.61) times the values of MG3B1 with epoxy resin. This indicates that when the CFRP strips embedded in cement based adhesive, a ductile behavior is obtained in comparison to the epoxy resin under monotonic loading as shown in Fig. 13(f). In case of repeated loading, the cumulative energy absorption of specimen G3B2 was decreased to (0.19) times that for specimen G3B1 while the ductility factor increased to (1.25) times that for G3B1 with epoxy resin as shown in Figs. 18 and 13(c). This means that the epoxy resin showed an excellent bonding behavior between FRP and concrete. From the Fig. 13(c), it can be seen that specimens tested under repeated loading showed a higher ductility and higher ultimate deflection compared with the monotonically-loaded specimen counterparts.

5. Conclusions

The experimental work in this study was carried out to investigate the behavior of reinforced concrete beams strengthened with NSM-CFRP strips under repeated and monotonic loadings considering different parameters such as the number of strips, groove size, type of loading, and two types of bonding materials. The following points highlight the main conclusions drawn based on the results of this study.

1. The NSM-CFRPs strengthening technique was effective to improve both the load carrying capacity and stiffness in comparison with non-strengthened beams. Using NSM-CFRP with one and three strips increased the ultimate load of beams to (1.47) and (1.68) respectively while the deflection was decreased to (0.45) and (0.37) times the values for the non-strengthened specimens under monotonic loading respectively. This due to the fact that CFRP strips prevented the widening and opening of cracks and enhanced the flexural stiffness.

2. The ductility factor and the cumulative energy absorption were decreased for specimens strengthened with one strip to (0.42) and (0.56) respectively and three strips to (0.22) and (0.41) times the values for non-strengthened beams respectively under monotonic loading. Therefore, the behavior was changed from ductile to brittle as a result of strengthening.

3. The main mode of failure for specimens strengthened with one and three strips under monotonic and repeated loading was debonding failure, either by interfacial debonding between epoxy and concrete or delamination failure of concrete at the level of longitudinal steel reinforcement.

4. Increasing the number of CFRP strips from one to three for strengthening specimens under repeated and monotonic loading not necessarily produces a proportional increase in load carrying capacity specially when the debonding failure control. The ultimate load was increased by (1.14) in monotonic loading and (1.31) times strengthened specimens in repeated loading.

5. Increasing the number of CFRP strips resulted in a reduction in the ductility factor by (29%) while the cumulative energy absorption increased by (22%) with respect to the reference strengthened specimens under repeated loading. Therefore, specimen strengthened with three CFRP strips with a total area of ($63\ \mathrm{mm}^2$) failed at a lower number of loading cycles compared with specimen strengthened with one strip with an area of ($21\ \mathrm{mm}^2$).

6. Increasing the groove size (depth of groove) from $1.5\mathrm{b}_\mathrm{b}$ to $2.2\mathrm{b}_\mathrm{b}$ didn't have a considerable effect on the ultimate load capacity. However, the use of small groove size increase the distance between CFRPs and longitudinal steel reinforcement which delays the debonding failure and a higher capacities may be achieved. However, the mode of failure also affected the maximum load carrying capacity.

7. Using a groove size of ($1.5\mathrm{b}_\mathrm{b}$) resulted a higher ductility and higher energy absorption. This led to an increase in the number of cycles until failure. Specimen with $1.5\mathrm{b}_\mathrm{b}$ groove size was failed after 40 cycles compared to a 36 cycles for specimen with a groove size of $2.2\mathrm{b}_\mathrm{b}$. It is not recommended to use a groove depth equal to two times the width of CFRP strips.

8. The mode of failure for specimens with $2.2\mathrm{b}_\mathrm{b}$ groove depth under monotonic and repeated loading was the concrete cover separation (premature debonding failure).

9. For beams with NSM-CFRP strips bonded with cement-based adhesive, an improvement was obtained in flexural strength strengthened with respect to the non-strengthened specimen. The ultimate load was increased to (1.82) times the value of the non-strengthened beam. Also, the ultimate deflection was reduced to (0.56) times the non-strengthened counterparts. However, using the cement-based adhesive decrease the composite action between CFRP strips and the concrete compared to epoxy resin.

10. For beams with cement-based adhesive a reduction in ductility factor and the cumulative energy absorption by (11%) and (22%) respectively was observed compared with non-strengthened specimen under monotonic loading.

11. Replacing epoxy resin with cement-based adhesive resulted in a decrease in ultimate load by (59%) and (61%) times that for beam with epoxy resin for monotonic and repeated loading respectively. This is due to a better bond properties and excellent penetration between epoxy resin and CFRP strips.

12. Replacing epoxy resin with cement based adhesive increased the ductility to (1.61) and (1.25) times that for

specimens bonded with epoxy resin for monotonic and repeated loading respectively. Specimen with cement-based adhesive failed with a higher number of cycles (which was up to 61cycles).

13. Replacing epoxy resin with cement-based adhesive reduced the cumulative absorption energy under repeated and monotonic loading by (81%) and (59%) compared to specimen with epoxy resin.

14. Powerful strengthening method was achieved by using epoxy resin in which an ultimate load increase of (4.49) times that for the non-strengthened specimen was obtained when using tensile reinforcement ratio equal to 0.44%. The mode of failure for this specimen was shear crack- induced debonding.

15. The principle mode of failure for specimen with cement-based adhesive tested under monotonic load was debonding between fibre and cement mortar while specimens tested under repeated loading failed by debonding between mortar and concrete followed by partial strip rupture.

16. A special attention should be given by the designers when using NSM-CFRP strengthening technique and choosing the suitable bonding material especially for structures subjected to a high load reversal such as cyclic or seismic loads in which a high ductility demand is required.

Acknowledgments

The authors wish to thank the staff of the Civil Engineering Laboratory of Al-Nahrain University for their support during the experimental part of this work.

References

ACI Committee 318 (2014), *Building Code Requirements for Structural Concrete*, (ACI 318M-14) and Commentary (318R14), Farmington Hills, Michigan, U.S.A.

ACI Committee 440 (2008), *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, Michigan, U.S.A.

Aidoo, J., Harries, K.A. and Petrou, M.F. (2004), "Fatigue behavior of carbon fibre reinforced polymer-strengthened reinforced concrete bridge girders", *J. Compos. Constr.*, **8**(6), 501-509.

Al-Abdwais, A. and Al-Mahaidi, R. (2016), "Bond behavior between NSM CFRP laminate and concrete using modified cement-based adhesive", *Constr. Build. Mater.*, **127**(1), 284-292.

Al-Abdwais, A.H. and Al-Mahaidi, R.S. (2017), "Bond properties between carbon fibre reinforced polymer (CFRP) textile and concrete using modified cement-based adhesive", *Constr. Build. Mater.*, **154**, 983-992.

Al-Mahmoud, F., Castel, A., François, R. and Tourneur, C. (2009), "Strengthening of RC members with near surface mounted CFRP rods", *Compos. Struct.*, **91**(2), 138-147.

ASTM C 39/C 39M (2005), *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, Annual Book of ASTM Standard.

ASTM C 78 (2002), *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*.

ASTM C109-02 (2002), *Standard Test Method for Compressive Strength of Hydraulic Cement Mortar*, Annual Book of ASTM Standard.

ASTM C496/C496M (2011), *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Balaguru, P., Nanni, A. and Giancaspro, J. (2008), *FRP Composites for Reinforced and Prestressed Concrete Structures: A Guide to Fundamentals and Design for Repair and Retrofit*, CRC Press.

British Standards Institution Part 2-Concrete (1997), *Methods for Specifying Concrete Mixes*, BS1881: Part 116 (1989), *Method for Determination of Compressive Strength of Concrete Cubes*, British Standards Institution.

Carolin, A., Nordin, H. and Täljste, B. (2001), "Concrete beams strengthened with near surface mounted reinforcement of CFRP", *Proceedings of the International Conference on FRP Composites in Civil Engineering*.

De Lorenzis, L., Nanni, A. and La Tegola, A. (2000), "Strengthening of reinforced concrete structures with near surface mounted FRP rod", *International Meeting on Composite Materials, Proceedings, Advancing with Composites*, Milan, Italy, May.

Dezhangah, M. and Sepehrinia, M. (2018), "The effects of different Frp/concrete bond-slip laws on the 3D nonlinear FE modeling of retrofitted RC beams-a sensitivity analysis", *Steel Compos. Struct.*, **26**(3), 347-360.

Ghafoori, N. (2009), *Challenges, Opportunities and Solutions in Structural Engineering and Construction*, CRC Press.

Hadi, A., Raheem, A. and Al-Abdwais, A. (2014), "Strengthening of concrete structure with near surface mounted carbon fibre reinforced polymer and cement based adhesive", Ph.D. Dissertation, Swinburne University of Technology, Australia.

Hashemi, S. and Al-Mahaidi, R. (2008), "Cement based bonding material for FRP strengthening of concrete structures", *Proceedings of the 11th Conference on International Inorganic-bonded Fibre Composites*.

Hong, S.N. and Park, S.K. (2016), "Energy dissipation capacity of reinforced concrete beams strengthened with CFRP strips", *Mech. Compos. Mater.*, **52**(2), 231-242.

Liang, J.F., Yu, D., Xie, S. and Li, J. (2017), "Flexural behaviour of reinforced concrete beams strengthened with NSM CFRP prestressed prisms", *Struct. Eng. Mech.*, **62**(3), 291-295.

Maalej, M. and Leong, K.S. (2005), "Engineered cementitious composites for effective FRP-strengthening of RC beams", *Compos. Sci. Technol.*, **65**(7), 1120-1128.

Panjehpour, M., Abang, A., Abang, A. and Aznieta, F.N. (2014), "Energy absorption of reinforced concrete deep beams strengthened with CFRP sheet", *Steel Compos. Struct.*, **16**(5), 481-489.

Rakhshanimehr, M., Esfahani, M.R., Kianoush, M.R., Mohammadzadeh, B.A. and Mousavi, S.R. (2014), "Flexural ductility of reinforced concrete beams with lap-spliced bars", *Can. J. Civil Eng.*, **41**(7), 594-604.

Sena-Cruz, J.M., Barros, J.A., Coelho, M.R. and Silva, L.F. (2012), "Efficiency of different techniques in flexural strengthening of RC beams under monotonic and fatigue loading", *Constr. Build. Mater.*, **29**, 175-182.

Sharaky, I.A., Torres, L., Comas, J. and Barris, C. (2014), "Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fibre reinforced polymer (FRP) bars", *Compos. Struct.*, **109**, 8-22.

Soliman, S.M., El-Salakawy, E. and Benmokrane, B. (2010), "Bond performance of near-surface-mounted FRP bars", *J. Compos. Constr.*, **15**(1), 103-111.

CC