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State of the art review: Flexural Strengthening of reinforced and pre-stressed concrete beams using Fiber reinforced polymers

A. Y. Soror [1], M. A. Tayel [2], and K. M. Heiza [3]
1. MS Candidate at Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt.
2. Professor of Reinforced Concrete Structures at Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt.
3. Professor of Reinforced Concrete Structures and Vice Dean for Community Services and Environmental Development at Faculty of Engineering, Menoufia University, Egypt.

ABSTRACT:

All over the world the concrete structure elements require rehabilitation or strengthening at certain times due to different reasons as Errors in planning or construction, increasing the service loads and others. In the last few decades the common material used for strengthening of concrete structural elements was fibre reinforced polymers FRP due to it`s High strength-to-density ratio, high levels of stiffness and chemical resistance. This paper presents the different techniques of strengthening of reinforced and pre-stressed concrete structural elements using FRP materials, the procedures of strengthening as surface preparation, adhesive curing and discuss the different modes of failures. This technique eliminates or reduces the crack width and growth rate, delay initial cracking, increase the flexural stiffness deflection and extend the fatigue life of RC beams. The best strengthening option in this case is pre-stressed carbon fibre reinforced polymer (CFRP).

ملخص البحث:

في جميع أنحاء العالم ، تتطلب عناصر المنشآت الخرسانية إلى إعادة التأهيل أو التدعيم في أوقات معينة نتيجة العديد من الأسباب مثل الأخطاء في التخطيط أو الإنشاء أوزيادة الأحمال التشغيلية وغيرها من الأسباب. في العقود القليلة الماضية تعتبر البوليمرات المدعمة بالألياف هي المادة الشائعة المستخدمة في تقوية العناصر الإنشائية الخرسانية نظرًا لأنها ذات مقاومة عالية مقارنتا بكثافتها ، وذات صلابة عالية ومقاومتها للمواد الكيميائية. يقدم هذا البحث الأنظمة المختلفة والمستخدمة في تدعيم المنشآت الخرسانية المسلحة وسابقة الجهاد بإستخدام البوليمرات المدعمة بالألياف ، توضيح خطوات التدعيم مثل تجهيز الاسطح ومعالجة المواد اللاصقة ومناقشة أنماط الإنهيار المختلفة. هذه التقنية تلاشي أو تقلل من عرض الشروخ ومعدل إستمراريتها داخل القطاعات ، وتأخير ظهور أول شرخ ، وزيادة جساءة وزيادة العمر الإفتراضي للكمرات تحت تأثير التحميل المستمر. يعتبر التدعيم بإستخدام البوليمرات المدعمة بالألياف سابقة الإجهاد هي أمثل طريقة للتدعيم.

Keywords: Pre-stressed; Reinforced concrete beams; Flexural strengthening; Near-surface mounted; Fiber reinforced polymers; Failure modes.

1. INTRODUCTION

Strengthening is the process of increasing the performance of existing structures more than the initial performance that the structure was designed on it [1, 2]. Existing structural elements after a certain period of time should be strengthened due to increases in working loads, unsuitable design and the need to increase the service period [3]. Two general methods for flexural strengthening with FRP are: the externally bonded EB system and the near-surface-mounted NSM system [5]. The basic concept of these two systems is to improve flexural strength and stiffness by adding FRP material to the concrete tensile surface. For the EB system, FRP sheets or plates are bonded to the concrete surface using epoxy adhesives [6, 7]. The NSM strengthening technique become an attractive method for strengthening reinforced concrete members [8- 14]. FRP bars or plates are inserted into grooves that is made in the concrete surface with a concrete saw with certain dimensions after that grooves are filled with epoxy adhesive to bond the FRP to the concrete [15]. The most advantages of NSM reinforcement does not required any surface preparation work except grooving; once the NSM reinforcement is protected by the concrete cover, it is then suitable to strengthen the negative moment regions of beams and slabs, a significant decrease of harm resulting from fire, mechanical damage and other effects, NSM is less prone to de-bonding from the concrete substrate. The bond behavior between concrete surface and composite carbon fiber reinforced polymer materials in NSM and EB technique was studied in [16].

2. Advantages And Disadvantages of (FRP) Composites Material

FRP composites material used in reinforced concrete element strengthening applications or as internal reinforcement. It's have a lot of advantages and disadvantages.

2.1. Advantages of (FRP) Composites Material

Composites are combinations of two or more materials (reinforcing elements and resin) that retain their identities while acting in concert. Fiberglass-reinforced polymer (FRP) composites are safe and reliable solutions, able to face tough conditions in various environments and have outperformed traditional materials for many years. Composites offer these important benefits:

- **Light Weight:** Composite parts help save weight compared to steel parts (up to 30 percent lighter) with similar thermo-mechanical properties.
- **High Strength:** Pound for pound, glass fibers are stronger than steel. Composites gain their strength when fibers are set within a resin matrix. Fibers carry the load while the resin spreads the load imposed on the composite.
- **Easy to Shape:** Composites can be molded into complex shapes at relatively low cost. This flexibility offers designers extensive latitude in new product design.
- **Integration of Functions:** Parts with multiple functions can often be made in a single step with composites.
- **Corrosion Resistance:** Composites provide long-term resistance to severe chemical and temperature environments. Composites are the material choice for outdoor exposure, chemical handling and severe environment service.
- **Durability:** Composite structures have an exceedingly long life span. Coupled with low maintenance requirements, the longevity of composites is a benefit when used in critical applications. After a half-century of use, many well-designed composite structures have yet to wear out.
- **Cost savings:** Thanks to their low weight and high mechanical properties, the use of composites in many applications reduces manufacturing, shipping and maintenance costs compared to traditional materials such as steel.

2.2. Disadvantages of (FRP) Composites Material

- Composites are more brittle than wrought metals and thus are more easily damaged. Cast metals also tend to be brittle.
- Repair introduces new problems, for the following reasons:
  1. Materials require refrigerated transport and storage and have limited shelf lives.
  2. Hot curing is necessary in many cases, requiring special equipment.
  3. Curing either hot or cold takes time. The job is not finished when the last rivet has been installed.
- If rivets have been used and must be removed, this presents problems of removal without causing further damage.
- Repair at the original cure temperature requires tooling and pressure.
- Composites must be thoroughly cleaned of all contamination before repair.
- Composites must be dried before repair because all resin matrices and some fibers absorb moisture.

3. Flexural strengthening using (FRP) composites

3.1. Strengthening methods

Two general methods for flexural strengthening with FRP composites are: the externally bonded (EB) system and the near-surface mounted (NSM) system. The basic concept of these two systems is to improve flexural strength and stiffness by adding FRP material to the concrete tensile surface. For the EB system, FRP sheets or plates are bonded to the concrete surface using epoxy adhesives. To improve the bond strength between the concrete and the FRP, the concrete surface is usually treated by sandblasting. For the NSM system, FRP bars or plates are inserted into a groove that is made in the concrete surface with a concrete saw. The groove is then filled with epoxy adhesive to bond the FRP to the concrete. Fig. 1 shows samples for strengthening techniques.

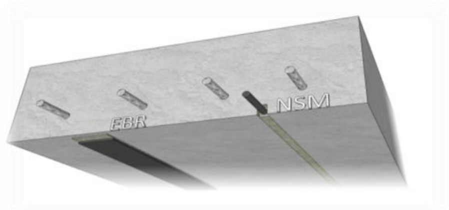


Fig. 1: (EB) and (NSM) Flexural strengthening technique.

3.1.1. Externally bonded technique

The use of bonded steel plates and bars for the strengthening and rehabilitation of reinforced concrete structures has been popular for years. Recently new FRP techniques with light weight, high strength, corrosion resistance are used in concrete structure strengthening and retrofitting as FRP sheets and laminates. The use of FRP sheets and laminates had been the common strengthening methods for RC structures. The bonding of FRP plates to the surface of reinforced concrete structures is now well established from of retrofitting with advanced design rules and mathematical models that quantify the de-bonding mechanisms. However, externally bonded plates tend to de-bond at low strains which limit effectiveness of this retrofitting technique. The performance of the FRP to the concrete interface in providing an effective stress transfer is an important issue. Indeed, a number of fatigue modes in FRP strengthened reinforced concrete members are directly caused by interfacial de-bonding between the FRP and the concrete. One of the failure modes, referred to as intermediate crack induced de-bonding, involves de-bonding which in initiates at a major cracks and propagated along the FRP concrete interface. Detailed procedures of (EB) FRP reinforcement installation to the concrete members shown in Fig. 2. Reference [17] presents more failure modes in comparison to conventional reinforced concrete (RC) beams strengthened with EB technique. Failure modes are classified into two types. The first type of failure includes the common failure modes such as concrete crushing and FRP rupture based on complete composite action. The second type of failure is a premature failure without reaching full composite action at failure. Table 1 and Fig. 3 summarize the failure modes of FRP strengthened beams with the EB system.

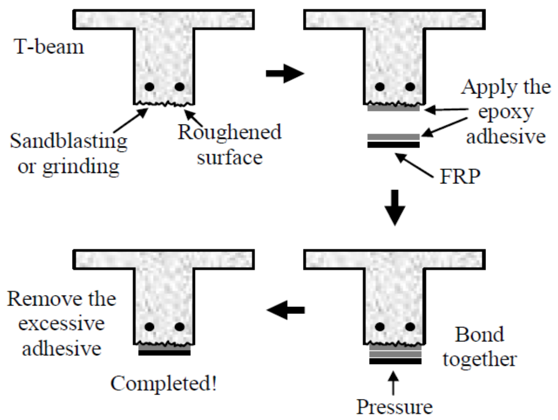


Fig. 2: Detailed procedures of EB strengthening technique [17].

Table 1: Description of failure modes for EB system [17].

Failure modes		Description
Case I: Full composite action	Concrete crushing	If premature failures are prevented, the ultimate flexural capacity of the beam is reached when either the FRP composite fails by tensile rupture or the concrete crushes in compression. This is similar to the classical flexural failure modes of RC beams except for the brittle failure of FRP rupture.
	FRP rupture	
Case II: Premature failure	End cover separation	Failure of the concrete cover is initiated by the formation of a crack at or near the plate end due to high interfacial shear and normal stresses caused by the abrupt termination of the plate.
	End interfacial delamination	This de-bonding failure is initiated by high interfacial shear and normal stresses near the end of the plate that exceed the strength of the weakest element (concrete or epoxy).
	Flexural crack induced de-bonding	Flexural crack induced de-bonding happens when the concentrated bond stress at the crack location exceeds the shear strength in the weakest layer.
	Shear crack induced de-bonding	Shear crack induced de-bonding occurs in the zone where both shear and bending moment are significant. It is caused by the combination of two mechanisms. The first one is similar to that of flexural crack induced de-bonding. The second is by the vertical movement of the inclined crack.

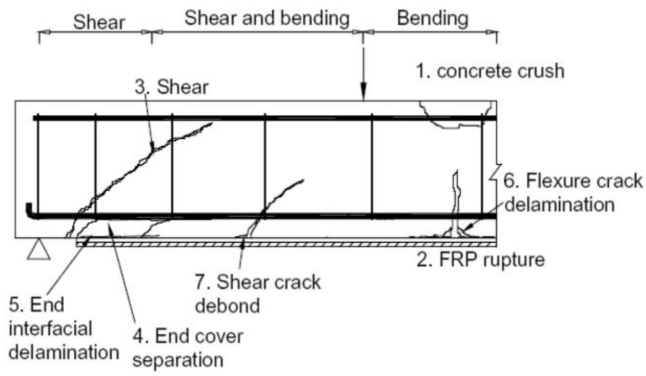


Fig. 3: Failure modes of EB strengthened beams [17].

Reference [18] conducted an experimental and numerical analysis to study the flexural response of ten reinforced concrete RC beam strengthened with carbon fiber reinforced polymer (CFRP) up to failure under monotonic and cyclic loads, Static and cyclic responses of all the beams were studied in terms of stiffness, strength, ductility ratio, energy absorption and associated with modes of failure. The theoretical moment-curvature relationship and the load-displacement response of the control and strengthened beams were predicted by using finite element analysis FEA software ANSYS. Results showed a good agreement between experimental and FEM as shown in Fig. 4 in addition to strengthening of RC beams using CFRP increase the flexural strength by about 18% to 20% for single layer and about 40% to 45% for two layers both static and compression cyclic loading; respectively.

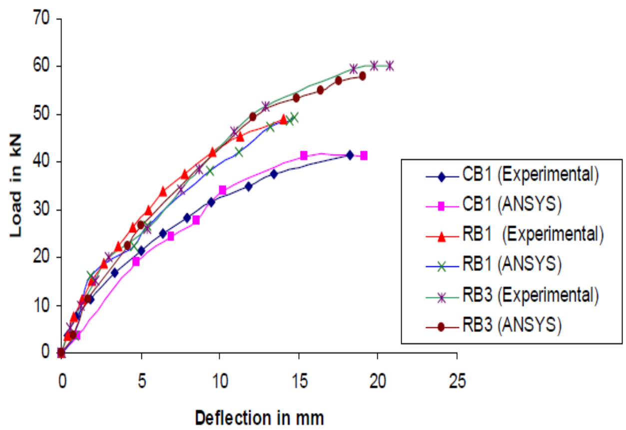


Fig. 4: Experimental and FEM load-deflection curves for beams [18].

Ceroni and Pecce, 2005, [19] conducted an experimental program to study the strength and ductility of RC beams strengthened with EB FRP sheets. An experimental program was conducted on RC beams strengthened with external flexural and flexural shear strengthening using fibre reinforced polymer (FRP) sheets [20]. (FRP) sheets consisting of glass FRP (GFRP) and carbon FRP (CFRP). The researcher studied the effect of different strengthening arrangements of CFRP and GFRP sheets on the strengthened RC beams. All beams were simply supported beams with a clear span of 1500 mm and tested under four-point bending up to failure, Fig. 5 and Fig. 6 shows the details and the Equipment location of the strengthened beams. Different modes of failure of flexural strengthened beams shown in Fig. 7. Results showed that strengthening of RC beams using EB CFRP sheets increase the overall flexural capacity of strengthened beams between 41% and 125% over the control beam.

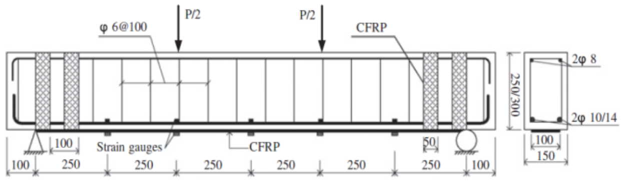


Fig. 5: Details of flexural strengthened beams.

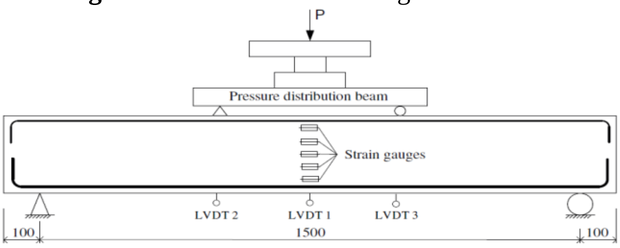
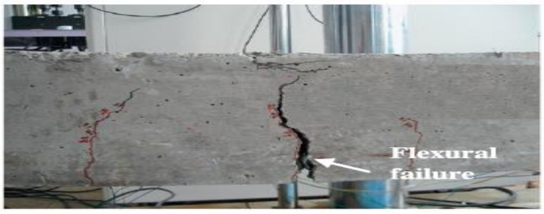
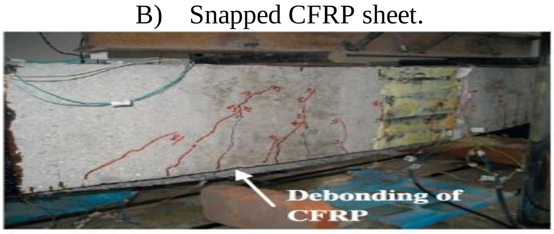


Fig. 6: Locations of equipment along the tested beams.



A) Flexural failure of the control specimen.

B) Snapped CFRP sheet.



C) CFRP debonding from mid-Span.

D) CFRP debonding under the loading point.

Fig. 7: Failure mode of flexural strengthened beams.

Reference [21] conducted an experimental study on five RC beams strengthened with CFRP laminated with different levels. Results showed that the addition of CFRP laminated to the tension bottom surface of the beams significantly increase the stiffness and ultimate capacity of beams. Reference [22] an experimental study was conducted to investigate the effect of width, multiple layers and strength of FRP sheets on strength and ductility of strengthened reinforced concrete beams in flexure. A total of eleven under-reinforced beams were tested, one beam considered as reference beam and the other ten beams were strengthened with different widths and numbers of FRP layers. Results showed that the use of single layer FRP wide sheets would increase the strength with a negligible reduction of ductility. Using multiple layers of wide FRP sheets yielded more increase of strength but reduced ductility of the beams. Multiple narrow strips of FRP will not add to the strength, but will reduce the deflection by reducing ductility. Table 2 shows the tested beams strengthening type, the failure loads and modes of failure of tested beams.

Table 2: Tested beams failure loads and modes of failure [22].

Beam	FRP Type	FRP Width	No. of Layers	Failure Mode	Ultimate Load (lbs.)	Load Increase
1	Non	N.A.	N.A.	Yielding of steel reinforcing bars	19300	N.A.
2	FRP-1	5"	5	Shear failure at FRP end	32050	66%
3	FRP-1	1"	5	FRP debonding	18986	-1.6%
4	FRP-2	1"	5	FRP debonding	19394	0.5%
5	FRP-2	5"	5	Shear failure at FRP end	29869	54%
6	FRP-1	1"	5	FRP debonding	19937	3.3%
7	FRP-1	5"	5	Shear failure at FRP end	31779	64%
8	FRP-1	5"	1	FRP rupture	26290	36.2%
9	FRP-1	5"	1	FRP rupture	23862	23.6%
10	FCV	5"	1	Shear failure at FRP end	28413	47.2%
11	FRP-2	5"	5	Shear failure at FRP end	29960	55.2%

3.1.2. NEAR SURFACE MOUNTED TECHNIQUE

The near surface mounted NSM FRP has become an attractive method for strengthening of reinforced concrete structure by increasing their flexure and shear strength. In this technique, the FRP reinforcement is bonded into grooves cut into concrete cover. The NSM FRP technique has been used in many applications and it present several advantages over the externally bonded FRP technique in strengthening concrete structures. The most advantages of NSM reinforcement does not required any surface preparation work except grooving; once the NSM reinforcement is protected by the concrete cover, it is then suitable to strengthen the negative moment regions of beams and slabs, a significant decrease of harm resulting from fire, mechanical damage and other effects, near surface mounted is less prone to de-bonding from the concrete substrate, and furthermore, the aesthetics of a strengthened structure with NSM reinforcement are virtually unchanged. Although the bond performance is greatly improved as compared with the EB system, it is still the key factor in the design of NSM FRP strengthened elements. There are two main interfaces in this technique, the bar-epoxy and the concrete epoxy, in which it is affected by factors which include FRP properties, FRP surface treatment, bar size, groove surface, groove geometry, adhesive, test setup and concrete properties. strengthening procedure in the NSM-steel technique, strengthening bars were placed into grooves cut in the concrete cover of the RC beams and bonded using epoxy adhesive groove filler. The installation of the strengthening with NSM bars began with cutting groove with the certain dimensions shown in Fig. 8 in to the concrete cover of the beam specimens at the tension face in the longitudinal direction. The groove was made using a special concrete saw with a diamond blade. A hammer and a hand chisel were used to remove any remaining concrete lugs and to roughen the lower surface of the groove. The groove was cleaned with a wire brush and a high-pressure air jet. The groove was half-filled with epoxy and then the steel bar was placed inside the groove and lightly pressed. This forced the epoxy to flow around the inserted steel bar. Epoxy was used to fill the groove and the surface leveled. To ensuring the epoxy achieved reach the full strength, the beam was allowed to cure for one week. Detailed procedures of (NSM) FRP reinforcement installation to the concrete members shown in Fig. 9.

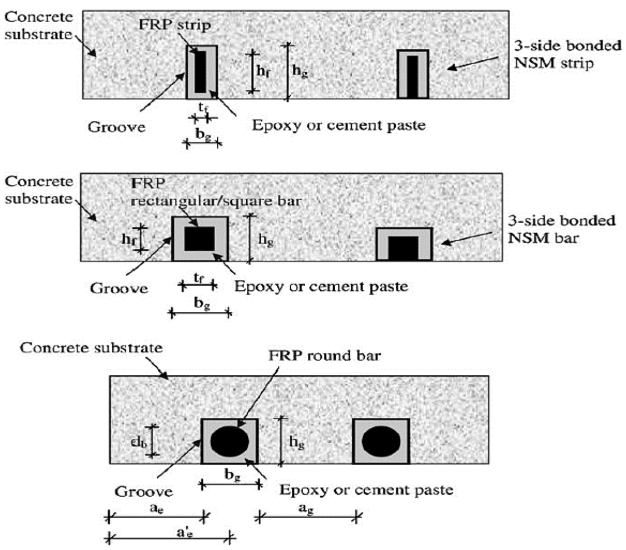


Fig. 8: Different NSM FRP installation and grooving details [13].

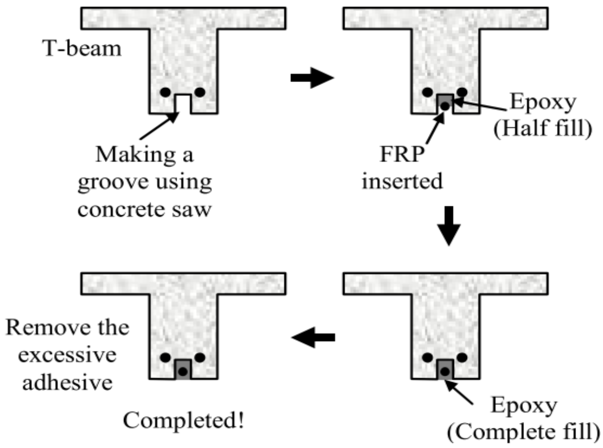


Fig. 9: Detailed procedures of NSM strengthening technique [17].

Reference [23] presents The possible failure modes of T RC beams flexural-strengthened with partially bonded NSM FRP reinforcement are of two types: those of conventional RC beams, including: the concrete crushing failure occurs when the concrete reaches its crushing strain before the FRP NSM reinforcement fails and FRP rupture generally after the yielding of internal steel bars as shown Fig. 10. Reference [24] presents the likeliness of a de-bonding failure depends on several parameters, among which the internal steel reinforcement ratio, the FRP reinforcement ratio, the cross-sectional shape and the surface configuration of the NSM reinforcement, and the tensile strengths of both the epoxy and the concrete. The different De-bonding failure modes of NSM bars and strips observed in tests on flexural-strengthened beams: (a) de-bonding at the bar–epoxy interface; (b) separation of concrete cover between two cracks in the maximum moment region; (c) separation of concrete cover over a large length of the beam; (d) separation of concrete cover starting from a cutoff section; (e) separation of concrete cover along the edge; (f) secondary loss of bond between epoxy and concrete; (g) secondary splitting of the epoxy cover as shown in Fig. 11.

A) Concrete crushing B) FRP rupture

Fig. 10: Failure modes of strengthened RC beams using NSM technique [23].

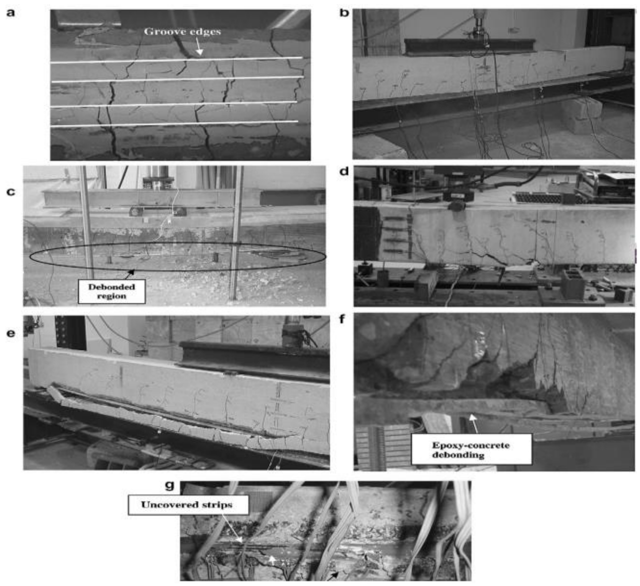


Fig. 11: Debonding failure modes of strengthened RC beams using NSM techniques [24].

Reference [25] conducted an experimental program to study the flexural behaviour of (RC) beams strengthened (NSM) technique using Carbon and glass fiber reinforced polymers (CFRP & GFRP). Fig. 12 and Fig. 13 shows the test set up and the cross sectional details; respectively. A ten full scale RC beams were divided to two groups as shown in table 3, the studied parameters were the used technique (NSM or Hybrid), type of strengthening material (carbon or glass), amount of FRP and the ratio of steel reinforcement. Results showed that the capacity of all strengthened beams increase in the ranging between 31% and 133% compared with the reference beams.

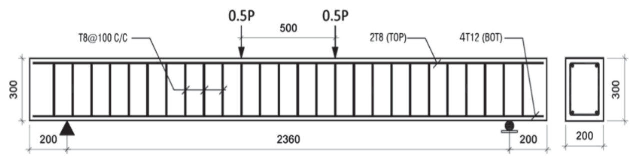


Fig. 12 : Test setup of tested beams [25].

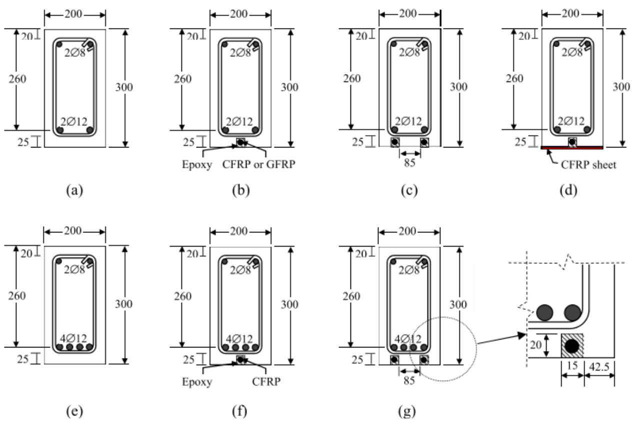


Fig. 13: tested beams cross sectional details [25].

Table 3: Experimental program of tested beams [25].

Group	Beam	Tension steel	Strengthening reinforcement
Group I	REF	2∅12	–
	CN1		1 CFRP bar
	CN2		2 CFRP bars
	GN1		1 GFRP bar
	GN2		2 GFRP bars
	CHYB		1 CFRP bar + 1 CFRP sheet
	GHYB		1 GFRP bar + 1 CFRP sheet
Group II	REF-II	4∅12	–
	CN1-II		1 CFRP bar
	CN2-II		2 CFRP bars

(Where C: carbon, G: glass, N: near surface mounted, HY: hybrid, B: beam, 1: one FRP bar, 2: two FRP bars, II: second group).

Reference [26] Studied the flexural behaviour of T-beams strengthened with NSM FRP reinforcements. References [27] and [23] conducted an experimental program to investigate the effect of a partially bonded NSM strengthening bars on the flexural behaviour of the tested beams. They showed that the stiffness of the beams at the post-yielding stage was decreased as the un-bonded length increased. The ultimate deflection in the partially bonded beams at failure showed only a slight increase (4.4% - 32.4%) compared to the fully bonded beam due to the complex behavior of the strengthened beams including FRP slip and concrete gradual failure. The ultimate load carrying capacity was slightly decreased (10.0% - 15.7%) as the un-bonded length increased because the failure mode was changed from FRP rupture to concrete crushing. Reference [28] modelling of reinforced concrete flexural members strengthened with near-surface mounted FRP reinforcement. Reference [29] presents a review on the flexural strengthening of RC beams with NSM CFRP strips. Reference [30] conducted an experimental program to investigate the efficiency of strengthening of RC beams by basalt fiber reinforced polymer bars (BFRP) using NSM technique in addition to determine the pull out behaviour of BFRP bars. The influences of groove size, bonded length and size of bars on the bond behavior were analysed. Results showed that there was no bond failure or debonding were observed in any test specimen. By increasing the percentage of NSM reinforcement bars the flexural capacity and effective pre-yield stiffness of the beam were increased, but with higher ratio of NSM reinforcement deflection and energy ductility reduced. It is observed that increasing the groove size did not increase the failure load as shown in Fig. 14.

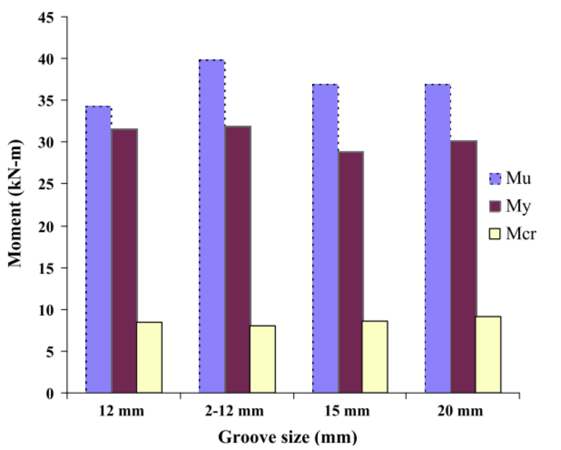


Fig. 14: Effect of groove size on the ultimate moment capacity [30].

3.1.3. PRE-STRESSED (FRP) STRENGTHENING SYSTEM

FRP composites are being investigated as an alternative material for pre-stressing due to their high tensile strength, low relaxation losses, and high corrosion resistance compared to conventional steel tendons. Numerous research and demonstration projects utilizing FRP pre-stressed tendons have been performed, and full scale FRP pre-stressed concrete bridges have been constructed around the world. A lot of researches are reported on the use of a pre-stressed FRP system for repair and strengthening purposes. The main advantage of this system is the recovery of the serviceability of structures, such as crack closure and deflection reduction. On the other hand, the disadvantages of pre-stressed FRP strengthening system are complicated installation procedure and low deformability compared to pre-stressed steel tendons. Initial intensive research with regard to the strengthening with pre-stressed EB FRP plates was performed. On the other hand, pre-stressed NSM system utilizing carbon FRP (CFRP) bars or plates has been recently investigated. Reference [31] applied a pre-stressed EB system to RC beams. Reference [32] showed that the using of pre-stressed NSM FRP strips can combine the advantages of these two strengthening methods and it thus becomes very attractive to further promote FRP applications in retrofitting concrete structures so they conducted an experimental program on seven rectangular RC beams under static loads up to failure. Fig. 15 describe the strengthening and pre-stressing system of the tested beams. The effect of the pre-stressing level, bond length, and the anchorage on the behaviour and failure modes of the tested specimens were analysed. Results showed that the ultimate capacity of the strengthened beams with pre-stressed NSM strips was increased ranged between 122 and 44.2% when compared to the un-strengthened beam and with non-pre-stressed FRP strips; respectively. Fig. 16 presents some of the failure mode for the tested beams.

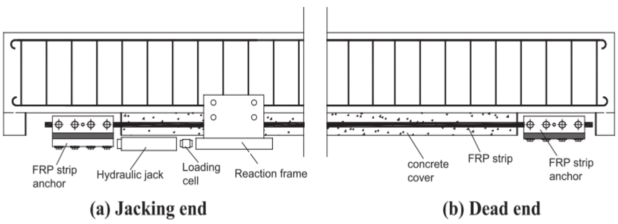
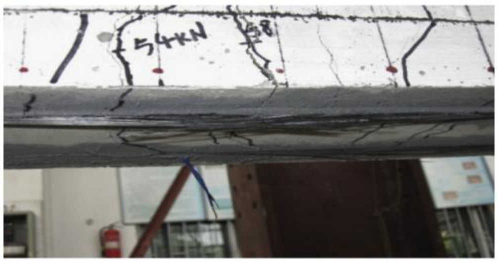


Fig. 15: Strengthening and pre-stressing system of the tested beam [32].

A) splitting of the concrete cover.

B) Epoxy-concrete interfacial de-bonding.



C) Rupture of CFRP strips.

Fig. 16: Failure modes of tested beams [32].

Reference [33] conducted an experimental program to evaluate the flexural response of pre-stressed concrete beams strengthened with externally bonded Fibre Reinforced Polymer (GFRP) laminates. A total of fourteen beams of 3 m length and 150 mm x 250 mm in cross-section were casted and tested under four-point loading bending up to failure. Fig. 17 shows the details of reinforcement of the tested beams. Seven beams were casted with M35 concrete grade and strengthened with three different GFRP laminates having two different thicknesses 3 mm and 5 mm, the other 7 beams were casted with M60 concrete grade and strengthened with three different GFRP laminates having two different thicknesses 3 mm and 5 mm as shown in table 4. The studied parameters were the concrete grade, the type and thickness of GFRP laminate.

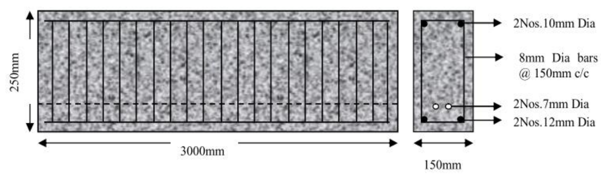


Fig. 17: Details of reinforcement of beams specimens [33].

Table 4: Experimental program of tested beams [33].

Beam Designation	% Steel Reinforcement	Grade of Concrete	GFRP	
			Type	Thickness
T	0.603	35	-	0
TC1	0.603	35	CSM	3
TC2	0.603	35	CSM	5
TU1	0.603	35	UDC	3
TU2	0.603	35	UDC	5
TW1	0.603	35	WR	3
TW2	0.603	35	WR	5
S	0.603	60	-	0
SC1	0.603	60	CSM	3
SC2	0.603	60	CSM	5
SU1	0.603	60	UDC	3
SU2	0.603	60	UDC	5
SW1	0.603	60	WR	3
TW2	0.603	60	WR	5

Note: CSM-Chopped Strand Mat; WR – Woven Roving; UDC - Uni-Directional Cloth

Results howed that The beams strengthened with 5mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 17.89%, 38.95% and 68.76%; respectively in ultimate load when compared to control beam and those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase upto 24.70%, 57.24% and 93.15%; respectively in ultimate load when compared to control beam. The beams strengthened with 3mm thick CSMGFRP, WRGFRP and UDCGFRP exhibit an increase of 7.41%, 37.49% and 81.20%; respectively in yield load when compared to control beam and those with 5mm thick CSMGFRP, WRGFRP and UDCGFRP laminates showed an increase up to 19.44%, 24.81% and 93.98%; respectively in yield load when compared to control beam. Fig. 18 shows the effect of GFRP laminates on various load levels for T-series beams.

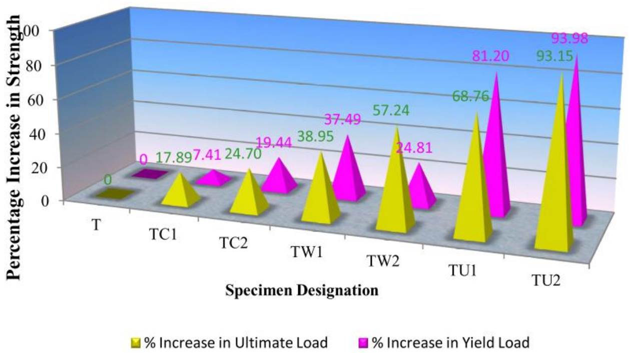


Fig. 18: Effect of GFRP plating on strength for t-series beams [33].

Reference [34] presents an experimental study to investigate the flexural response of large-scale RC beams strengthened in flexure with NSM CFRP bars tensioned against the beam. The studied parameter was the effect of different the pre-stressing level from 0% to 60% of the ultimate strength of the CFRP on the overall flexural response of the beams. Fig. 19 shows the system of pre-stressing of NSM bars. Results showed that the deflection in beams B2-0%, B2-20%, B2-40%, and B2-60% at the cracking load 18.4 kN (4.1 kip) of beam B2-0% were 1.64 mm, 0.9 mm, 0.78 mm, and 0.27 mm (0.065 in., 0.036 in., 0.031 in., and 0.010 in. Fig. 20 presents the load deflection response of tested beams.

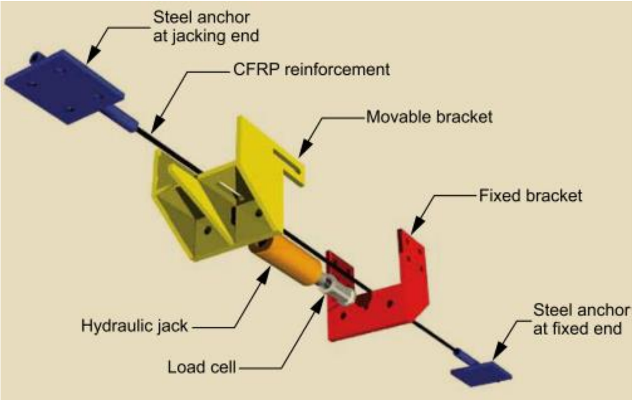


Fig. 19: Components of prestressing system [34].

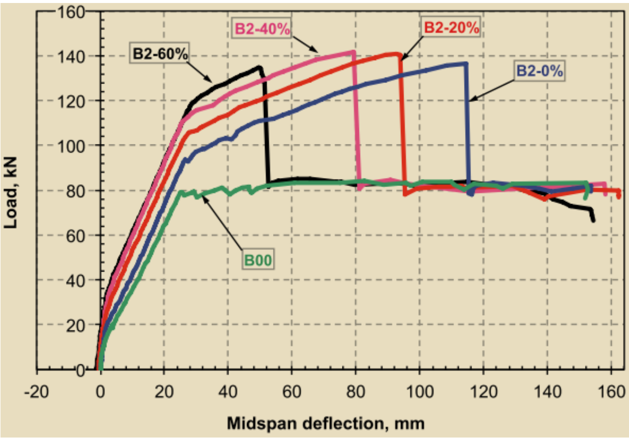


Fig. 20: load midspan deflection for all beams [34].

Reference [35] presents an experimental program to evaluate the influence of the pre-stressing technique on the flexural behaviour of reinforced-concrete (RC) beams strengthened with near-surface-mounted (NSM) carbon-fiber-reinforced-polymer (CFRP) laminates. Reference [36] conducted an experimental program on RC Beams Strengthened with Pre-stressed CFRP NSM Tendon using new pre-stressing system to solve the bond failure model featuring EBR and NSMR methods. Reference [37] conducted an experimental and analytical model to investigate the effectiveness of strengthening (RC) beams with pre- stressed (NSM) (CFRP) bars on eight RC beams. One un-strengthened beam was used as reference beam, four beams were strengthened with pre-tension NSM CFRP bars and the last three beams were strengthened with post-tension NSM CFRP bars. the strengthening performance of the RC beams strengthened with pre-tensioned bars according to filler type reveals that the Pre-E-SC-1 specimen shows concrete cracking, steel yielding, and maximum loads that are 53.9%, 24.6%, and 8.9% greater; respectively, than those of the Pre-M-SC-1 specimen. For RC beams strengthened with varied numbers of post-tensioned CFRP bars the Post-M-SC-2 specimen show that concrete cracking, steel yielding, and maximum loads are 18.0%, 29.4%, and 22.3%; respectively greater than those of the Post-M-SC-1 specimen. Fig. 21 shows the load-deflection behaviour of the tested beams.

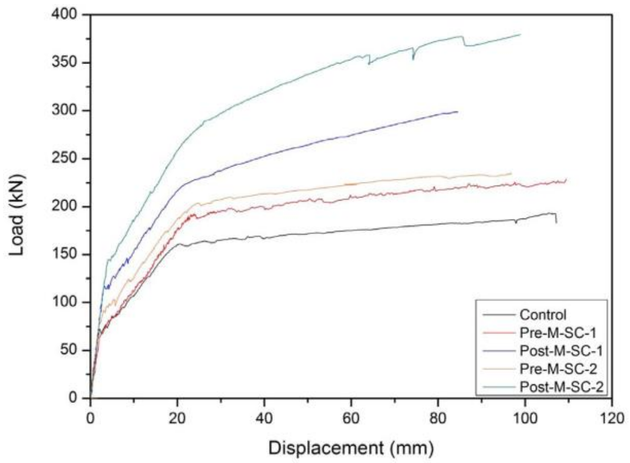


Fig. 21: Load-Deflection behaviour of the tested beams [37].

A 3D Finite element analysis FEA model using ABAQUS program was conducted for detailed analysis of the bending performance of RC beams strengthened by pre-stressed NSM systems. Fig. 22 and Fig. 23 shows the FEA model parts and the comparison between the experimental and the FEA results for the control beam. A parametric study was developed first, to investigate the influence of reinforcement length, the pre-stressing force was maintained at 120 kN. In these cases, the reinforcement lengths of the CFRP bar were 4.4 m (73%), 5.0 m (83%), and 5.6 m (93%). Second, to study the effect of pre-stressing, the reinforcement length was set to 5.0 m. The pre-stressing forces were 40% (96 kN), 50% (120 kN), and 60% (144 kN) of the tensile strength of the CFRP bar. The effect of reinforcement length of CFRP bar was show increases in the range of 58.6–75.0% in concrete cracking load level, 33.7– 59.1% in steel yielding load level, and 47.4–70.5% in maximum load level.

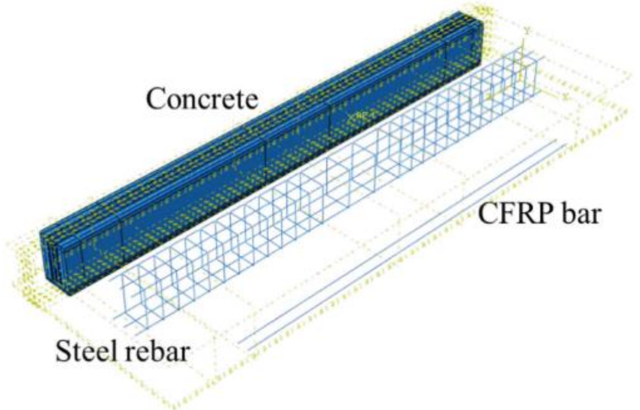


Fig.22: FEA model parts [37].

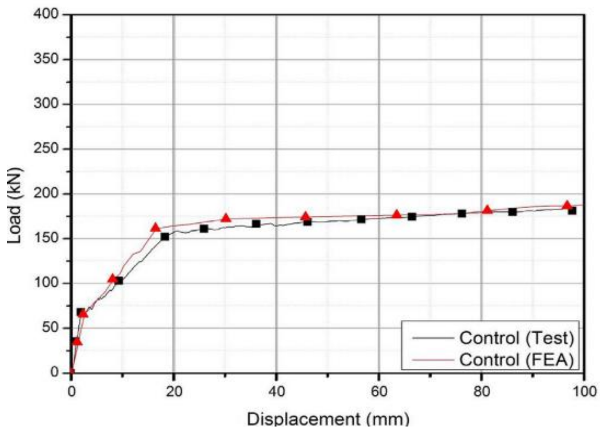


Fig. 23: Comparison of Experimental and FEA load – deflection curve for control beam [37].

4. CONCLUSION

In this paper presents a review of current and relevant studies on strengthening of reinforced and pre-stressed concrete beams using FRP. This study covered the experimental programs and finite element simulation, adhesive curing, Surface Preparation, modes of failure and load-deflection response for different strengthening techniques and parameters. The following conclusions can be obtained from the current study:

1. By increasing the percentage of NSM bars reinforcement the flexural capacity and effective pre-yield stiffness were increased, but the deflection and energy ductility were decreased with higher ratio of NSM reinforcement.
2. The strengthening effect of the pre-tensioned NSM strengthening system on the RC beam, in which anchorage was not used, was insignificant because of significant pre-stress losses. The strengthening effect on the RC beam improved by the post- tensioned NSM strengthening, for which anchorage was installed, because the anchorage minimized the pre-stress losses of the CFRP bars.
3. The bond failure between the NSM reinforcement bars and the surrounding material could be at the Bar-Epoxy, or Epoxy- concrete interfaces, and bond deficiency causing epoxy cover splitting as described. A Bar-Epoxy interface bond failure could be interfacial or cohesive shear failure in the filler.

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