# RETROFITTING OF REINFORCED CONCRETE BEAMS USING ADVANCED COMPOSITE OVERLAYS

*Ahmad Abdel Hamid, Professor, Drexel University, Philadelphia, USA*

*Hany Elshafie, Assistant Professor, Ain Shams University, Cairo, Egypt*

*El-Sayed Nasr, Professor, Ain Shams University, Cairo, Egypt*

*Ezat Fahmy, Professor, The American University in Cairo, Cairo, Egypt*

## Abstract

There is a considerable number of existing reinforced concrete structures in Egypt that do not meet current design standards because of inadequate design and/or construction or need structural upgrading to meet new seismic design requirements. Inadequate performance of this type of structures is a major concern from public safety standpoint. This paper presents an experimental research program aimed at developing a retrofitting technique that utilizes locally available high strength, lightweight, corrosion resistance advanced composites for retrofitting existing reinforced concrete beams of frame structures in Egypt. The proposed technique consists of applying Glass Fiber Composite Laminates (GFCL) to the bottom surface and sides of the concrete beam to increase its stiffness and flexural strength. A total of six full scale reinforced concrete beams were constructed, tested under four points loading representing full dead and live loads and then unloaded to dead load. Under this dead load the beams were retrofitted with GFCL and then loaded till failure. An increase of 8 to 60% in beam flexural strength was achieved using GFCL depending on amount and configuration of the laminates. An increase in the post-cracking flexural stiffness of 75 to 175% was obtained for the retrofitted beams. This study clearly demonstrated the effectiveness of the proposed technique in retrofitting reinforced concrete buildings in Egypt.

Keywords: beams, composite laminates, glass fibers, loading stage, reinforced concrete, retrofitting, stiffness, strength

## Introduction and Background

There is a considerable number of existing reinforced concrete structures in Egypt that do not meet current design standards because of inadequate design and/or construction or need structural upgrading to meet new seismic design requirements. Retrofitting of flexural concrete elements are traditionally accomplished by externally bonding steel plates to concrete. Although this technique has proved to be effective in increasing strength and stiffness of reinforced concrete elements, it has the disadvantages of being susceptible to corrosion and difficult to install. Recent development in the field of composite materials, together with their inherent properties, which include high specific tensile strength good fatigue and corrosion resistance and ease of use, make them an attractive alternative to steel plates in the field of repair and strengthening of concrete elements. The effectiveness of using Fiber Reinforced Composites in increasing strength and stiffness of reinforced concrete flexural elements is evident from results of previous research work (Bazaa et al.1996, Chajes et al. 1995, Grace. Et al. 1999(a&b), Swamy et al. 1995) and observed behavior of field applications (ACI 440-1996, Meier et al. 1995). The literature review showed that Carbon Fiber Composites were the most frequently used system in previous research and retrofitting field applications. Although this material has superior properties which include very high tensile strength accompanied with a reasonable modulus of elasticity (almost equals that of steel); its high cost is still one of the main disadvantages, which limits its use as a replica to externally bonded steel plates in retrofitting applications. On the other hand, the Glass Fiber Composites (GFC) are comparatively cheap and have high tensile strength but with relatively low modulus of elasticity (about one-third that of carbon and reinforcing steel). Although, GFC seem to be attractive and cost-efficient for retrofitting flexural reinforced concrete elements, few research work were conducted to study the behavior of such systems. When using GFC to retrofit flexural reinforced concrete elements, careful attention should be paid not only to the strength of the retrofitted element but also to its stiffness and ductility. Moreover, the stage of loading at which the retrofitting is carried out is one of the important aspects that impacts the effectiveness of the retrofitting process.

In the research reported in this paper, the feasibility of using Glass Fiber Composite Laminates (GFCL) locally available in the Egyptian market in retrofitting flexural reinforced concrete elements is studied.

## Experimental Program

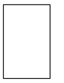
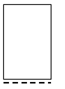
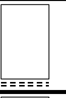
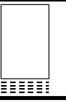
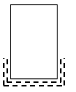
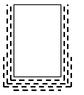
***Scope***

The experimental study represented herein was carried out at the Reinforced Concrete Laboratory, Faculty of Engineering, Ain Shams University, Egypt. Six full-scale reinforced concrete beams were constructed and tested as simple beams under four points loading. The details of the test specimens are shown in Table 1 and Fig. 1. One of the test specimens B1 served as the control beam which was loaded continuously till failure without retrofitting. The other five beams were tested under full dead and live loads and then unloaded to dead load. Under this load, the beams were retrofitted using different amounts and configurations of GFCL as shown in Table 1 and Fig. 1.

***Test Specimens***

All beams have lengths of 2.30m and cross-sectional dimensions of 150mmx300mm as shown in Fig. 1. All beams have the same flexural (longitudinal) reinforcement of two 14-mm diameter deformed steel reinforcing bars as bottom reinforcement and two 10-mm diameter deformed steel reinforcing bars as top reinforcement as shown in Fig. 1. The flexural reinforcement is chosen to provide an under-reinforced section with a flexural-dominating behavior. The shear reinforcement consisted of 8-mm diameter plain mild steel reinforcing bars as closed stirrups spaced every 150mm along the beam longitudinal axis as shown in Fig. 1. The shear reinforcement was designed to provide enough shear strength greater than the shear forces associated with the flexural failure of all retrofitted beams.

**Table 1.** Test Matrix

| **Beam Code** | **Amount and configuration of GFCL** | | | | | | | **Configuration** |
|---|---|---|---|---|---|---|---|---|
| | $T_f$ [1] **(mm)** | $N$ [2] | $W$ [3] **(mm)** | $A_f$ [4] **(mm$^2$)** | $\rho_f$ [5] **(%)** | $\rho_{f-eqv.}$ [6] **(%)** | $R$ [7] | |
| 1 | ------- | | | | | | |  |
| 2 | 0.08 | 1 | 1- 150 | 12 | 3.9 | 3.9 | 12.5 |  |
| 3 | | 2 | 2 – 150 | 24 | 7.8 | 7.8 | 6.25 |  |
| 4 | | 4 | 4 – 150 | 48 | 15.6 | 15.6 | 3.12 |  |
| 5 | | 2 | 2 – 300 | 48 | 15.6 | 14.6 | 6.25 |  |
| 6 | | 4 | 2 – 750<br>1 – 300<br>1- 150 | 156 | 50.6 | 34.6 | 4.9 |  |

[1] $T_f$ : Equivalent thickness of longitudinal fibers in single layer of GFCL.

[2] $N$ : Number of layers

[3] $W$ : Widths of layers

[4] $A_f$ : Equivalent cross sectional area of longitudinal fibers = $T_f * \sum W$

[5] $\rho_f$ : Fibers content = Equivalent cross sectional area of longitudinal fibers as percentage of cross-sectional area of bottom flexural reinforcing steel bars ( $A_s$ =area of two 14-mm diameter = 308mm$^2$)

[6] $\rho_{f-eqv.}$ = Equivalent fibers content =

$$\frac{\sum \text{Fibers Content} * \text{Distance from fibers centroid to top surface of concrete section}}{\text{Thickness of concrete section}}$$

[7] $R$ : Bond index = $\dfrac{\text{Width of contact surface between FCL and concrete substrate - mm}}{\text{Equivalent cross sectional area of longitudinal fibers } (A_f) \text{ - mm}^2}$

All beams and control specimens were cast and wet cured in the laboratory. The beams were then stored under standard laboratory conditions until time of testing. Before testing, concrete surfaces where GFCL are to be bonded were roughened using a motor-driven wire brush.

The 28-day design strength of the concrete used in constructing the beams was 30 MPa. During casting, six cubes were prepared and tested at the time of testing the beams. The average cube compressive strength was 33 MPa. Test specimens were prepared from the reinforcing bars used and were tested in tension. The average mechanical properties of the reinforcing bars are summarized in Table 2.

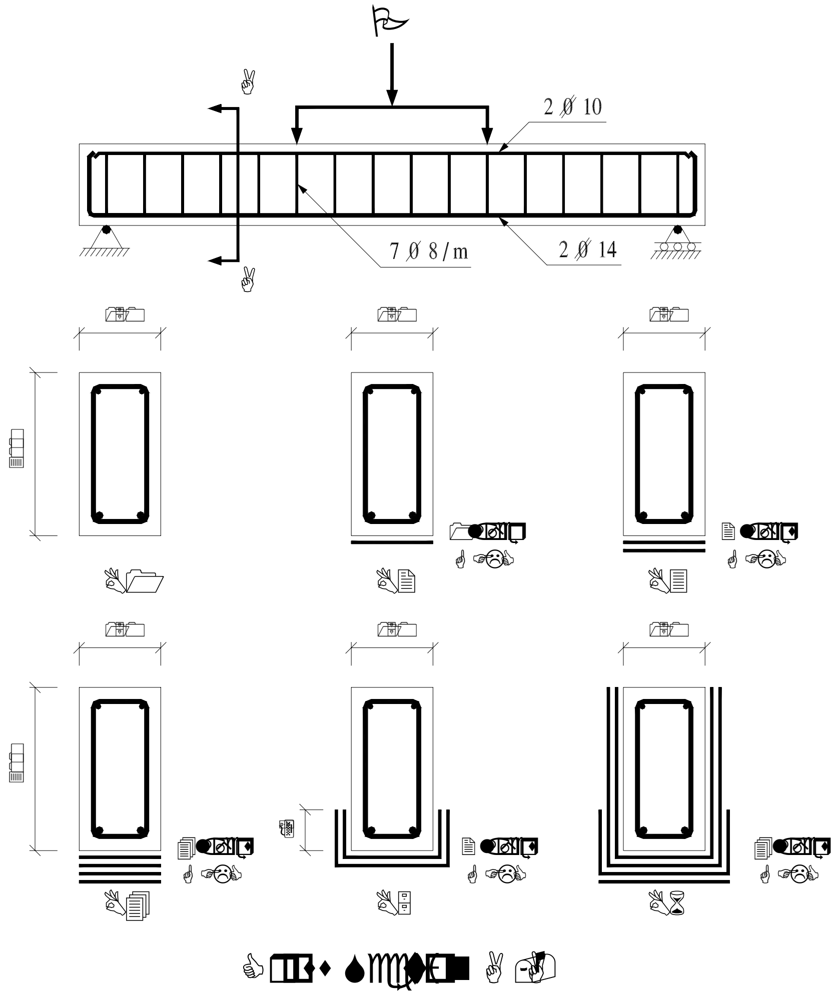



**Figure 1.** Details of Test Beams

**Table 2.** Mechanical Properties of Reinforcing Bars

| Type | Diameter (mm) | Yield stress (MPa) | Ultimate strength (MPa) | Elongation* (%) |
|---|---|---|---|---|
| Deformed bars (Flexural rft.) | 14 | 409 | 632 | 19.1 |
| | 10 | 395 | 658 | 23.4 |
| Plain bars (Shear rft.) | 8 | 338 | 507 | 23.7 |

* Based on gage length of 10 times the diameter.

### *Glass Fiber Composite Laminates*

The composite material consisted of glass fibers and polyester resin. The glass fibers used were Type E in the form of bi-directional woven mat with 50% of the fibers running in the longitudinal direction and the other 50% running in the transverse direction perpendicular to the longitudinal fibers. The amount of fibers was $0.04 g/cm^2$ for the mats used in this research. Since the fibers are the load-carrying element in GFCL, the effective thickness of GFCL layer is equal to the equivalent thickness of fibers running parallel to the load direction (the longitudinal fibers in the case of retrofitted beams). The equivalent thickness of the longitudinal fibers ($T_f$) is calculated based on the following equation:

$$T_f = \frac{\alpha \; w}{\gamma} \tag{1}$$

Where,

$\alpha$ = Fraction of fibers in longitudinal direction
$w$ = Weight per unit area of fiber mat
$\gamma$ = Relative density of fibers = 2.5

Coupon specimens were tested in tension to determine the mechanical properties of GFCL and to draw its stress-strain curve. The tested specimens showed linear elastic behavior up to failure as shown in Fig. 2. The mechanical properties of the tested specimens are given in Table 3.

**Table 3.** Mechanical Properties of GFCL

| Specimen | Ultimate strength* (MPa) | Ultimate strain* mm/mm | Modulus of elasticity* (GPa) |
|---|---|---|---|
| 1 | 1206 | 0.0197 | 60.3 |
| 2 | 1350 | 0.0240 | 56.2 |
| 3 | 1161 | 0.0205 | 53.0 |
| Average | 1239 | 0.0214 | 56.5 |

* Calculations are based on equivalent thickness of longitudinal fibers.

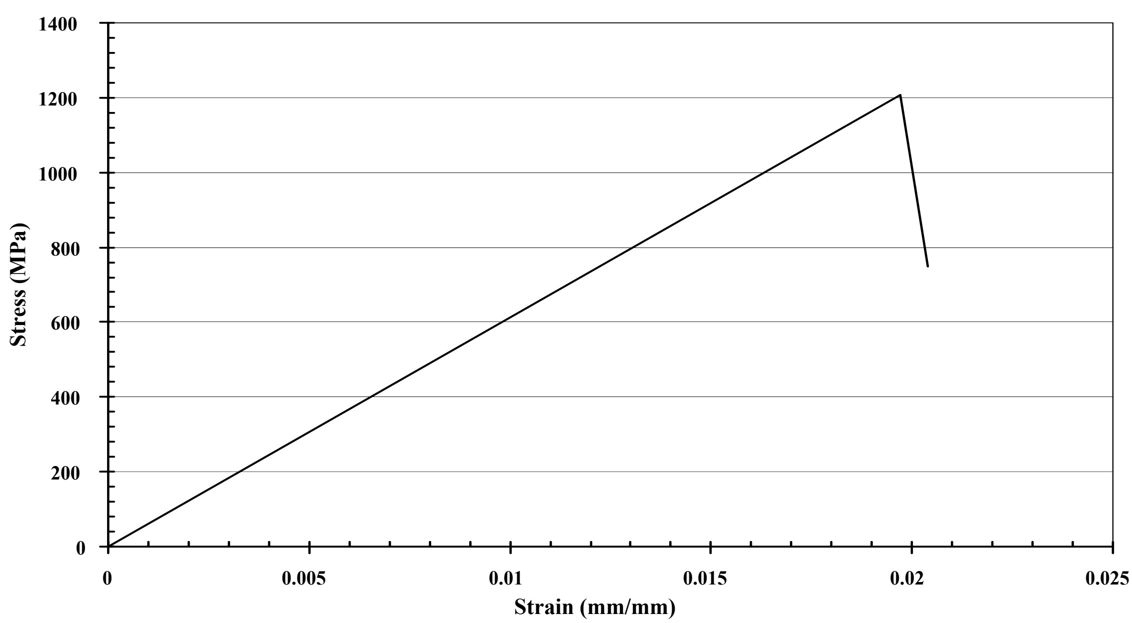



**Figure 2.** Typical Stress-Strain Curve of GFCL Coupon

### *Test Setup and Instrumentation*

Figure 3 shows a schematic of the test setup. The specimens were tested as simple beams under four point loading. The load was applied monotonically using 500-kN capacity hydraulic jack. The load was measured using 450-kN capacity load cell. Linear Variable Displacement Transducers (LVDTs) were used to measure the vertical displacements at mid-span and at the supports and the concrete compressive strain at the extreme top fiber of the beam middle section. A data acquisition system connected to a PC-computer was used to collect the data and the load–deflection curve of the test specimen was displayed on the screen in real time during testing to help monitoring the beam behavior.

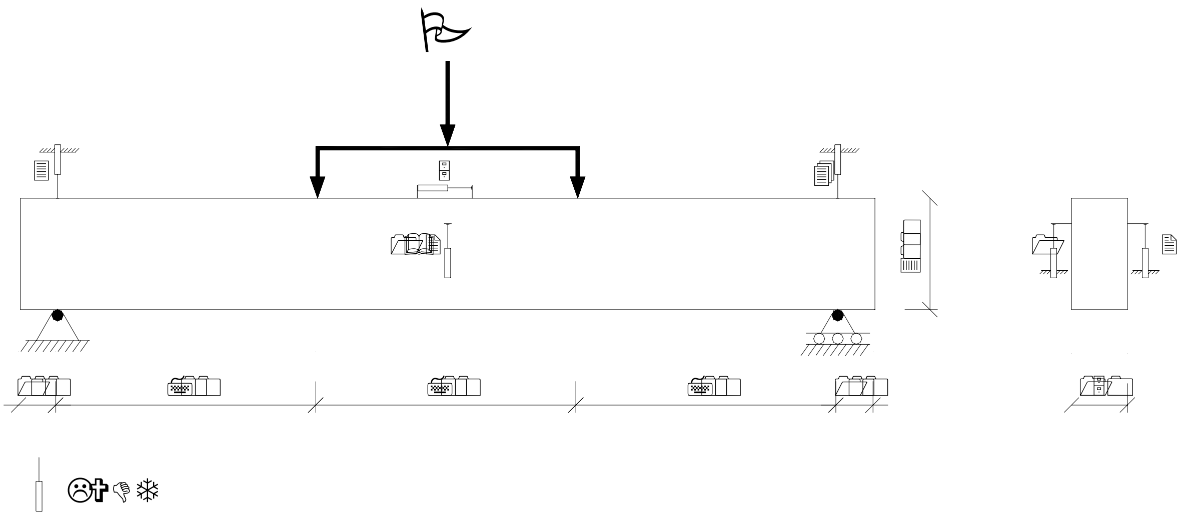


**Figure 3.** Test Setup and Instrumentation

### *Test Procedure and Retrofitting Application*

Except for the control beam B1, which was loaded monotonically up to failure, all other beams were loaded up to about 67% of the ultimate load of the control beam (load equivalent to full service dead and live loads). During loading, the specimen was visually inspected and cracks were marked. The specimen was then unloaded to about 50% of ultimate load of the control beam (load equivalent to service dead load only). Under this load the beams were retrofitted using different amounts and configurations of GFCL as shown in Table 1 and Fig. 1. The GFCL was applied on the concrete surfaces by a hand lay-up process. The concrete surfaces were brushed to remove all loose materials. The polyester was then mixed with the initiator and the concrete surfaces were coated using roller. At the same time, the glass fibers mat was saturated with the resin and then was applied to the coated concrete surfaces. In cases of multi-layer retrofitting, the first layer was allowed to stiffen for about half an hour before applying the next layer utilizing the same technique followed for the first layer. The GFCL was allowed to cure for 24 hours, then the loading continued monotonically up to failure.

## Test Results

All beams failed in flexural mode as intended. The control beam B1 failed by yielding of flexural reinforcement and the test was stopped before crushing the concrete. The failure modes of the retrofitted beams as detected by visual inspection during testing are as follows:

- Beams B2, B3, and B5 failed by fracture of GFCL as shown in Fig. 4.
- Beam B4 failed by delamination between the GFCL and the substrate concrete as shown in Fig. 5.
- Beam B6 failed by crushing of concrete in the compression zone followed by the fracture of GFCL as shown in Fig. 6.

Table 4 summarizes the failure modes and the ultimate loads of the test specimens. Figure 7 shows the load-deflection curves of the test specimens.

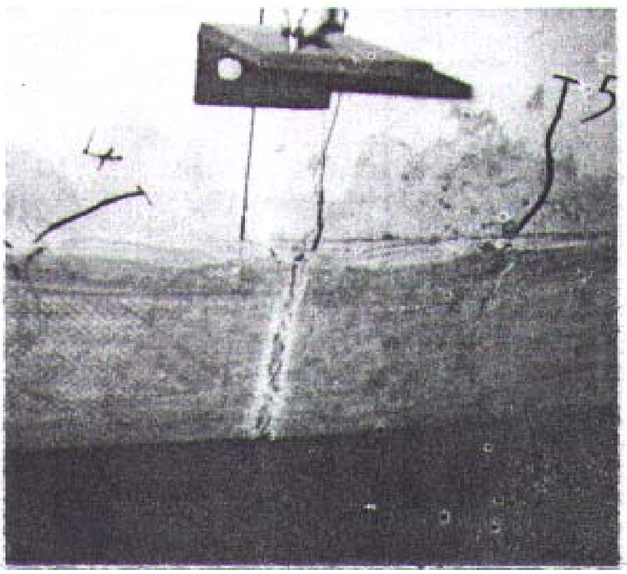


**Figure 4.** Failure Mode for Beam B5 (typical failure mode for beams B2, and B3)

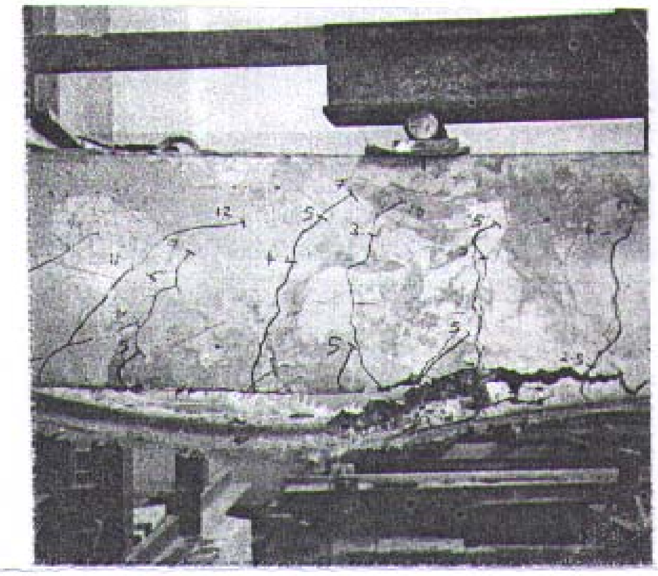


**Figure 5.** Failure Mode for Beam B4

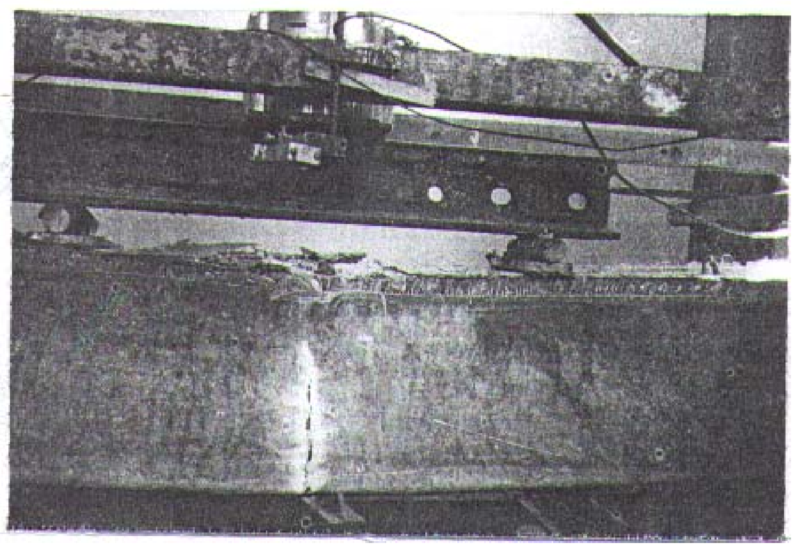


**Figure 6.** Failure Mode for Beam B6

**Table 4.** Failure Modes and Ultimate Loads

| Beam Description | | Failure Mode | Ultimate Load | |
|---|---|---|---|---|
| Code | $\rho_{f-eqv.}$ (%) | | Absolute (kN) | % of Control Beam Ult. Load |
| B1 | ------- | Yield of bottom flexural reinforcement | 108 | 100 |
| B2 | 3.9 | Yield of bottom flexural reinforcement followed by fracture of GFCL | 117 | 108 |
| B3 | 7.8 | | 133 | 123 |
| B4 | 15.6 | Yield of bottom flexural reinforcement followed by delamination of GFCL | 142 | 131 |
| B5 | 14.6 | Yield of bottom flexural reinforcement followed by fracture of GFCL | 145 | 134 |
| B6 | 34.6 | Yield of bottom flexural reinforcement followed by crushing of concrete then finally fracture of GFCL | 173 | 160 |

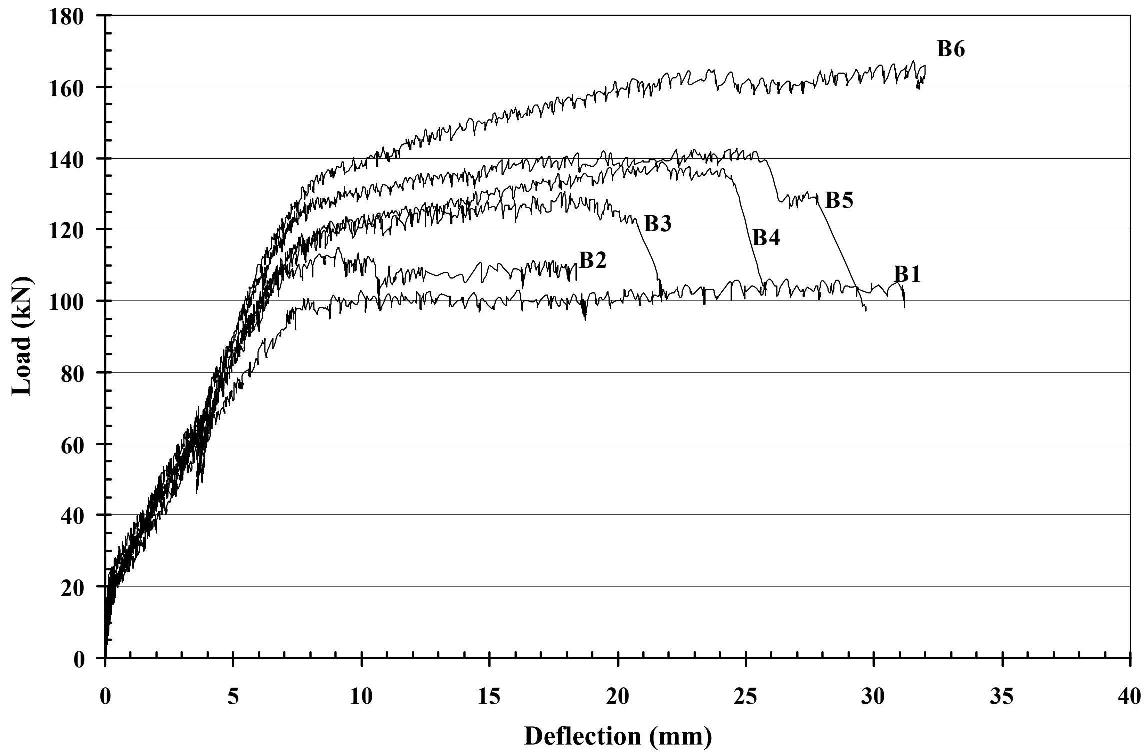



**Figure 7.** Load-Deflection Curves

## Discussion of Test Results

***Failure Modes***

All beams failed in flexural dominated mode as expected since the beams were under-reinforced and the stirrups were calculated to suppress shear failure under increased flexural capacity due to GFCL reinforcing. As shown in Figs.3 and 4, crack patterns are characterized by well-distributed flexural (vertical) cracks along the middle third of the beams. At failure, one of the major flexural cracks widened up significantly. Few diagonal (shear) cracks developed the in outer thirds. However, these cracks were not significant and did not widen up with loading.

As shown in Table 4 and Figs. 4 to 6, beams with relatively low fibers contents (beams B2, B3, and B5) failed in a tensile mode by fracture of GFCL, while beam B6 with high fibers content failed by crushing of concrete followed by fracture of GFCL. Beam B4, which has the lowest bond index (*R*), failed by delamination of GFCL from the concrete. This is a result of the high shear stress developed along the contact surface between the GFCL and the substrate concrete surface.

***Load-Deflection Curves***

In order to facilitate examining and understanding the load-deflection curves of the beams, each curve is idealized as ploy-line curve, see Fig. 9. The idealized curve is characterized by the following distinctive four stages:-

Stage (I): Uncracked stage: Extending from zero load up to the cracking load.

Stage (II): Cracking-yielding stage: Extending from the cracking load up to a load corresponding to yielding of steel reinforcement. For the retrofitted beams, this stage is divided into the following three sub-stages:

- Stage (II-1): Pre-retrofitting stage: Extending from the cracking load to the service load. (about 67% of ultimate load of the control beam).
- Stage (II-2): Unloading stage: Extending from the service load to a load equivalent to dead load only (about 50% of ultimate load of the control beam).
- Stage (II-3): Post-retrofitting stage: Extending from the dead load to a load equivalent to yielding of reinforcing bars ($P_y$). This stage is presented by a bi-linear curve (part (II-3a) and part (II-3b) as shown in Fig. 9).

Stage (III): Yielding-peak load stage: Extending from the yield load up to the peak load ($P_u$).

Stage (IV): Post peak stage: Extending from the peak load up to the end of the test.

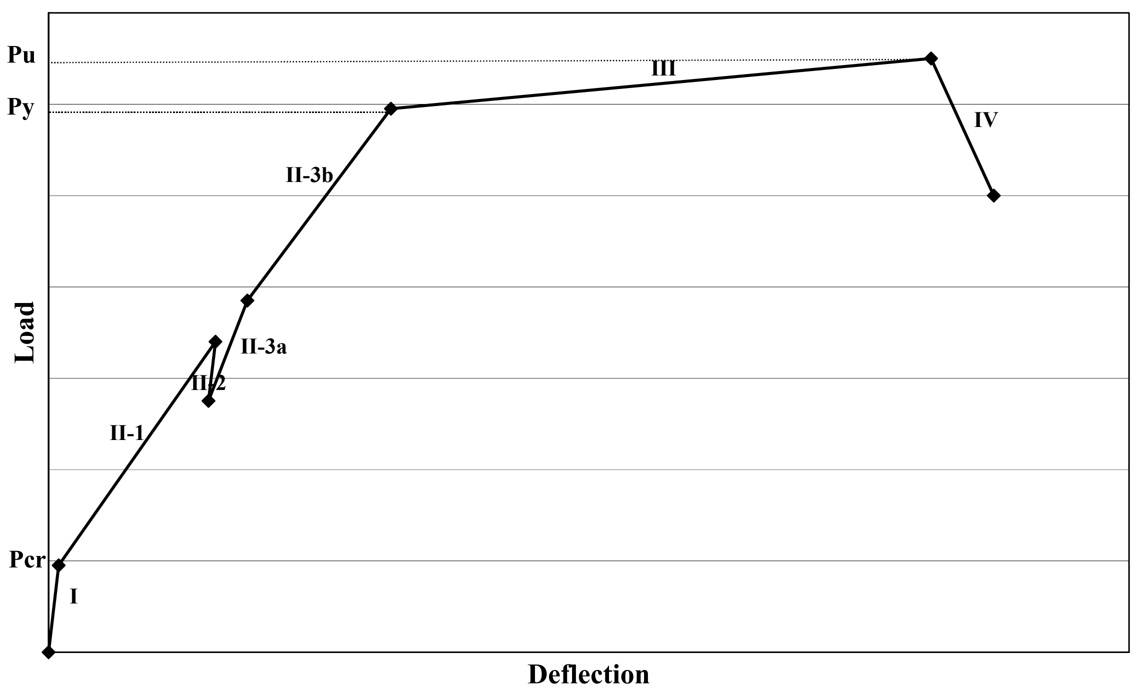



**Figure 9.** Idealized Load-Deflection Curve

The behavior of the beams can be discussed through an examination of the load-deflection curves shown in Fig. 7.

Uncracked stage, and cracking-yielding stage (up to unloading stage)

Since all the parent beams were identical, the behavior of the beams was almost the same up to unloading stage as shown in Fig. 7.

Cracking-yielding stage (post-retrofitting stage)

At early loading stage (part II-3a in Fig. 9), the post-retrofitting stiffness of the retrofitted beams increased significantly compared to stiffness of control beam B1 and the pre-retrofitting stiffness. The ratios of early post-retrofitting stiffness (part II-3a) to pre-retrofitting stiffness (part II-1) of the retrofitted beams range from 1.75 to 2.75. It is noticeable that the increase in early post-retrofitting stiffness is not sensitive to the amount of fibers (fiber contents) since this stiffness increases is attributed to the effect of the externally bonded composites on closing the cracks.

At the later loading stage (part II-3b in Fig. 9), the post-retrofitting stiffness dropped to a value almost equal to pre-retrofitting stiffness. This indicates that the effectiveness of externally bonded composites on increasing the stiffness of the retrofitted beams reduces with loading. This could be attributed to the high deformation level in the fibers as a result of the relatively low modulus of elasticity of this type of fiber compared to that of reinforcing steel. It is also noted that late post-retrofitting stiffness increased slightly with the increase of fiber content.

The yield load (load at the end of part II-3b, Fig. 9) increased with the increase of fiber contents as in Fig. 7 while the corresponding deflection is almost the same. The increase in the yield load of the retrofitted beams as percentage of that of control beam ranges between 10% for beam B2 to 38% for beam B6. The increase in the yield load is proportional to the increase in fibers content.

Yielding-peak stage

The yielding-peak stiffness of the retrofitted beams increased with the increase of fibers content. The ratios of yielding-peak stiffness of retrofitted beams B2 to B6 to that of control beam B1 range from 2 for beam B2 with equivalent fibers content ($\rho_{f-eqv.}$) of 3.9% to 9 for beam B6 with equivalent fibers content of 34.1%. In the post-yielding stage, there was no appreciable contribution of the yielded steel reinforcement to the beam stiffness and therefore the stiffness of the retrofitted beams depends mainly on the amount of fibers.

The peak (ultimate) load of the retrofitted beams increased proportionally with the increase of fibers content as shown in Fig. 7. The increase in the ultimate load of the retrofitted beams relative to that of control beam ranges from 9% for beam B2 to 56% for beam B6. It is noted that the effect of the retrofitting using GFCL on the behavior in yielding-peak stage is more pronounced compared to the effect on cracking-yielding stage (post-retrofitting stage). This is attributed to the fact that glass fibers have relatively low modulus of elasticity and therefore their contribution becomes effective only at high deformation levels.

The deflection corresponding to peak load for retrofitted beams is considerably less than that for the control beam. The peak load deflection of the retrofitted beams as percentage of that of the control beam ranges from 60% to 80%. This implies that the retrofitted beams possess less ductility (measured by deflection at peak load to deflection at yield) compared to un-retrofitted beams. This is a result of the brittleness nature of failure modes for retrofitted beams (either by fracture of fibers at relatively low strain (beams B2, B3, and B5), delamination of GFCL from concrete (beam B4), or crushing of concrete in the compression zone (beam B6)). It is interesting to notice that the deflection corresponding to peak load, and hence ductility, for retrofitted beams failed by fracture of GFCL (beams B2, B3, B5) increased with the increase of fibers content as shown in Fig. 7. This can be explained by the fact that curvature of beam section at fracture of the fibers (corresponding to peak load deflection) increases with the increase of the fibers content (as a result of increasing the depth of the compression zone to balance the increased tension force) leading to the increase in peak load deflection.

Post peak stage

As shown in Fig.7, the post peak behavior of beams B2 to B5, which failed by fracture (tensile failure mode) or delamination of GFCL, had dramatic decrease in their loading capacity. On the other hand, beam B6, which failed by crushing of concrete in compression zone, had a slow rate of post peak load degradation. It is to be noted that applying the GFCL along the full depth of beam B6 (including the compression zone) may had some confining effect on the concrete which improved the ductility of concrete in compression.

## Conclusions and Recommendations

Based on the test results presented in this paper, the following conclusions and recommendations are drawn:

1- An increase of 8 to 60% in beam flexural strength and an increase of 75 to 175% in post-cracking flexural stiffness were achieved by retrofitting the beams using 3.9 to 34.1% GFCL, respectively.
2- Applying the GFCL along the full depth of the beam (including the compression zone) increased the bond of GFCL to concrete and enhanced the concrete ductility as a result of the confining effect.
3- The effect GFLC retrofitting on increasing the strength and stiffness in the yielding-peak stage was more pronounced compared to the effect on cracking-yielding stage (post-retrofitting stage). This is attributed to the fact that glass fibers have relatively low modulus of elasticity and therefore their contribution becomes effective only at high deformation levels.
4- The retrofitted beams possessed less ductility compared to the unretrofitted beams. This is a result of the brittleness nature of the failure modes of the retrofitted beams (either by fracture of fibers at relatively low strain, delamination of GFCL from concrete, or crushing of concrete in the compression zone).
5- For the retrofitted beams failed in a tensile mode (by fracture of fibers), strength, stiffness, and ductility increased proportionally with the increase of fibers content.
6- For the most efficient utilization of GFCL, it is recommended to use the amount of fibers content which results in a balanced condition (i.e. fibers fracture at the same time of crushing of concrete).
7- In order to achieve full capacity of the laminates and to avoid brittle failure by delamination, special attention should be paid to provide adequate anchorage length for the fibers either longitudinally or transversely.

## Acknowledgements

The American University is acknowledged for supporting the test program. The beams were constructed and tested in the Reinforced Concrete Laboratory of Ain Shams University. The instrumentation and data acquisition system of the Properties and Testing of Materials Laboratory of Ain Shams University were used in the test. The use of the test facilities and equipment of the college of Engineering of Ain Shams University is gratefully acknowledged.

## References


1 Bazaa, I. M., M. Missihoun, and P. Labossiere (1996), "Strengthening of Reinforced Concrete Beams with CFRP Sheets," Proceedings of the First International Conference on Composites in Infrastructures (ICCI'96), Tucson, Arizona, USA, January 1996, pp 746-759.

2 Chajes, M. J., T. A Thomson, JR, and B. Tarantino (1995), " Reinforcement of Concrete Structures Using Externally Bonded Composite Materials," Proceedings of the second International RILEM Symposium (FRPRCS-2), August 1995, pp 501-508.

3 Grace, N. F., A. K. Soliman, G. Abdel-Sayed, and K.R. Saleh (1999a), "Strengthening of Continuous Beams Using Fiber Reinforced Polymer Laminates," Proceedings of the Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures, ACI International SP-188-57, 1999, pp 647-658.

4 Grace, N. F., G. A. Sayed, A. K. Soliman, and K.R. Saleh (1999b), "Strengthening Reinforced Concrete Beams Using Fiber Reinforced Polymer (FRP) Laminates," ACI Structural Journal/ September- October 1999, pp 865-874.

5 Swamy, R. N., and P. Mukhopadhyaya (1995), "Role and Effectiveness of Non-Metallic Plates in Strengthening and Upgrading Concrete Structures," Proceedings of the second International RILEM Symposium (FRPRCS-2), August 1995, pp 473-482.

6 American Concrete Institute, Committee 440 (1996), "State-of-the-art report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures,".

7 Meier, U., and A. Winistorfer (1995), "Retrofitting of Structures Through External Bonding of CFRP Sheets," Proceedings of the second International RILEM Symposium (FRPRCS-2), August 1995, pp 465-472.