STRENGTHENING AND REPAIR OF REINFORCED CONCRETE BEAMS IN FLEXURE USING GFRP SHEETS

By
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ABSTRACT

Strengthening and repair techniques using bonded fiber reinforced plastic (FRP) sheets have been used as a new technology for strengthening and repair reinforced concrete members. This technique is practically efficient method and very attractive alternative compared to the conventional methods due to the high strength-to-weight ratio, relative high stiffness, and ease of application of the FRP.

This work presents an experimental program that aims to study the behavior of reinforced concrete beams strengthened and repaired in flexure using externally glued glass fiber reinforced plastic (GFRP) sheets. Twenty-four reinforced concrete beams were used in this study. The test parameters included three ratios of steel tension reinforcement, and the number of layers of GFRP sheets and their shape. Three beams were preloaded up to 0.7 the ultimate load (0.7 Pu) other three were preloaded beyond the ultimate load (Pu). The results showed an increase in beam flexure strength ranging between 10 % and 60 % and also showed an increase in cracking load. Two failure modes were observed (sheet debonding failure and flexure compressive failure), depending on the ratio of steel tension reinforcement and hence the beam yield strength. In both cases, the sheet finally debonded due to excessive deformation. A theoretical calculation (for ultimate load) based on the flexure theory was made and showed good agreement when compared to the experimental results.

1-INTRODUCTION

Bonding external FRP sheets to the tensile faces of reinforced concrete beams is an efficient method for strengthening and repair of these beams. Some researchers have studied this method [1-7]. The advantages of this method include its simplicity, ease of construction, besides the advantages of these new materials which include very high tensile strength and sufficient modulus of elasticity (for carbon fiber, generally equal to that of steel). One of the main disadvantages of these materials is their relatively high cost. The glass fiber sheets are relatively cheap with a reasonable tensile strength and modulus of elasticity approximately equal to one third that of steel.

Flexural strengthening of reinforced concrete beams using GFRP sheets has been studied by a few of researches [8-10]. In this research, reinforced concrete beams are strengthened or repaired in flexure using external GFRP sheets and polyester adhesive available in Egypt. The experimental results showed the load carrying capacity and the debonding mechanism of GFRPS. From these results, it becomes possible to determine failure criteria of the strengthened beams and to use calculation models based on flexure theory in estimating the ultimate capacity of the strengthened beams with GFRPS.

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2-EXPERIMENTAL PROGRAM

Twenty-four beams with rectangular cross section of 12 cm wide and 20 cm deep and a total length of 240 cm with effective span 220 cm were tested. Fig. (1) and table (1) show the details and properties of these beams.

Three tension reinforcement ratios 0.77%, 1.1% and 1.96% (represented 2 ϕ 10, 2 ϕ 12 and 2 ϕ 16 respectively) were used. Beams B1, B9 and B17 were reference unstrengthened beams for each tension reinforcement ratio. These reference beams (B1, B9 and B17) are repaired after testing as reference beams and after releasing the load then tested under the name B1R , B9R and B17R respectively. Four types (A, B, C and D) of strengthening and repairing details were used in this work as shown in Fig.(1) and table (1).

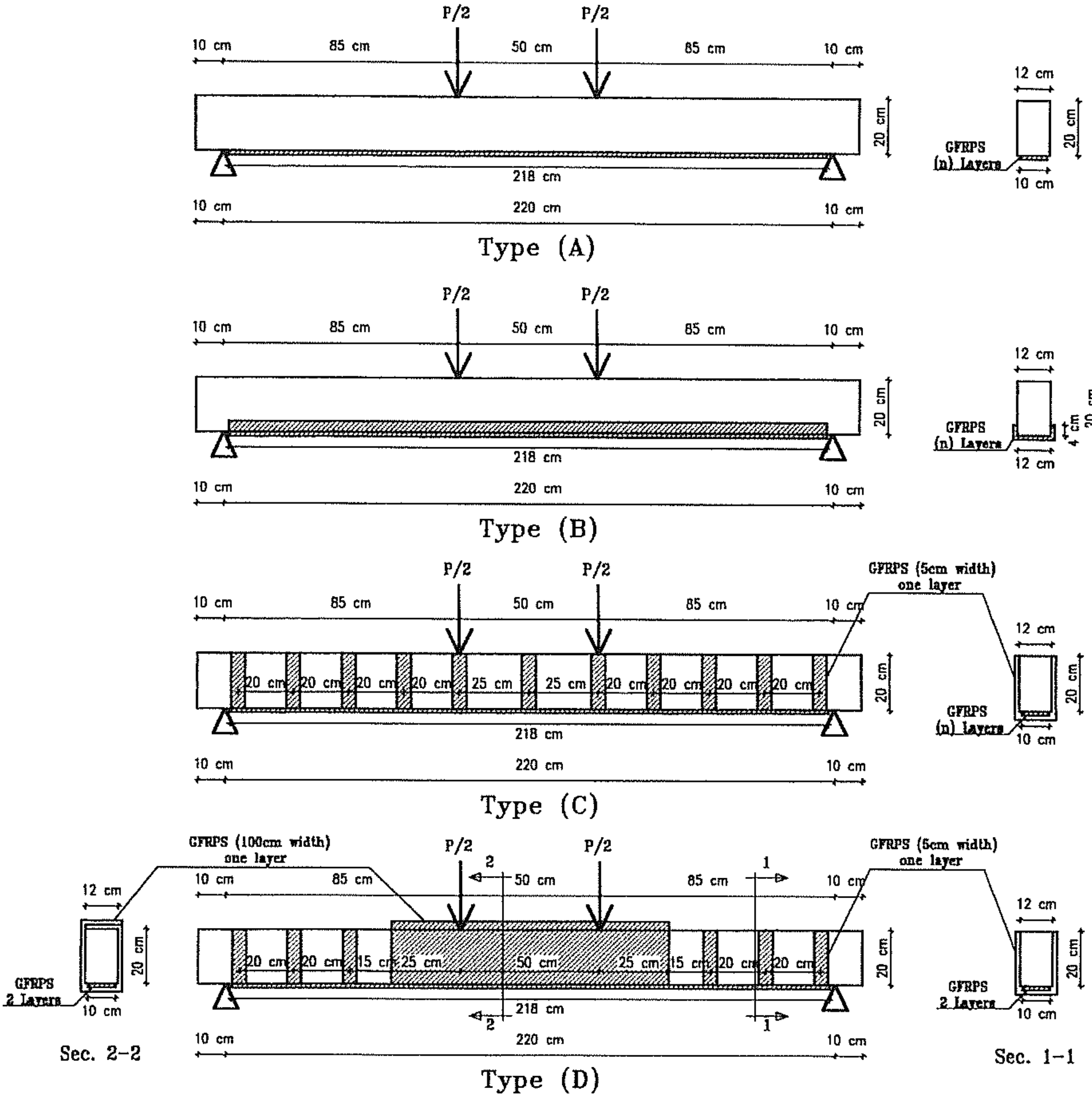

Fig. (1) strengthening and repairing details of tested beams.

Table (1) properties of the tested beams:

Beam No.	Tension RFT (ratio)	Yield of tension RFT Fy (t/cm^2)	Type of strengthening and repairing	No. of layers (n)	Application of GFRP sheets
B1	2 ϕ 10 (0.77%)	4.6	—	—	—
B1R			C	2	After loading to Pu
B2			A	2	Before loading
B3			C	2	After loading to 0.7Pu
B4			A	4	Before loading
B5			B	2	Before loading
B6			B	1	Before loading
B7			C	2	Before loading
B8			C	4	Before loading
B9	2 ϕ 12 (1.11%)	4.7	—	—	—
B9R			C	2	After loading to Pu
B10			A	2	Before loading
B11			C	2	After loading to 0.7Pu
B12			A	4	Before loading
B13			B	2	Before loading
B14			B	1	Before loading
B15			C	2	Before loading
B16			C	4	Before loading
B17	2 ϕ 16 (1.96%)	4.9	—	—	—
B17R			C	2	After loading to Pu
B18			A	2	Before loading
B19			C	2	After loading to 0.7Pu
B20			A	4	Before loading
B21			B	2	Before loading
B22			B	1	Before loading
B23			C	2	Before loading
B24			D	2	Before loading

Compression reinforcement 2 ϕ 10 with $Fy = 4.6\ t / cm^2$
Stirrups 10 ϕ 8 / m with $Fy = 2.9\ t / cm^2$

Type A is a horizontal sheets wide 10 cm which is applied to the bottom face of the beam by polyester adhesive. The length of the sheet is 118 cm i.e. 1 cm apart from the support each side. The number of the layers (n) of these sheets is two or four. Type B is a U shape sheet of horizontal part 12 cm wide along the bottom face of the beam and two vertical parts 4 cm wide along the two sides of the beam. The sheets lengths and the method of applying to the beam is similar to type A . The number of layers (n) is one or two to have the same areas of type A . Type C is similar to type A with additional external strips of GFRP with 5 cm wide and distance 20 cm apart in general along the beam length. Each strip is a U shape covered the horizontal bottom face and the two sides of the beams with horizontal length 12 cm and two vertical length 20 cm each. Type D is similar to type C but in the middle of the beam and with length 1 m along the beam a GFRP sheet is applied around the four faces of the beam and with over lap length 12 cm at the top face of the beam as shown in Fig. (1).

All the tested beams are strengthened before loading except B1R, B9R and B17R, as explained before, and B3, B11 and B19, which preloaded up to 0.7 ultimate load (0.7Pu). The GFRP sheets were applied to these beams after the release of the load.

The concrete compressive strength used for casting the beams varied between 305 and 390 kg/cm^2. High strength deformed bars of yield strength 4.6, 4.7, 4.9 t/cm2 for 10 , 12 and 16 mm bar diameters respectively were used.

Glass fiber reinforced plastic sheets of 0.13 mm thickness (available in Egypt) were used to strengthen the tested beams. The tensile strength and elastic modulus of these sheets were 22 t/cm^2 and 724 t/cm^2 respectively. GFRP sheets were bonded to the concrete surface using polyester component adhesive mortar. The tensile strength of the mortar is about 320 kg/cm^2. The GFRP sheets were applied above proper surface preparation. The surface was prepared by removing dust, loose concrete and cement paste.

The beams were tested in four-point bending with the load application points as shown in fig.(2) . During the test, the point load, beam deflection, flexural strains in the mid span and crack development was measured.

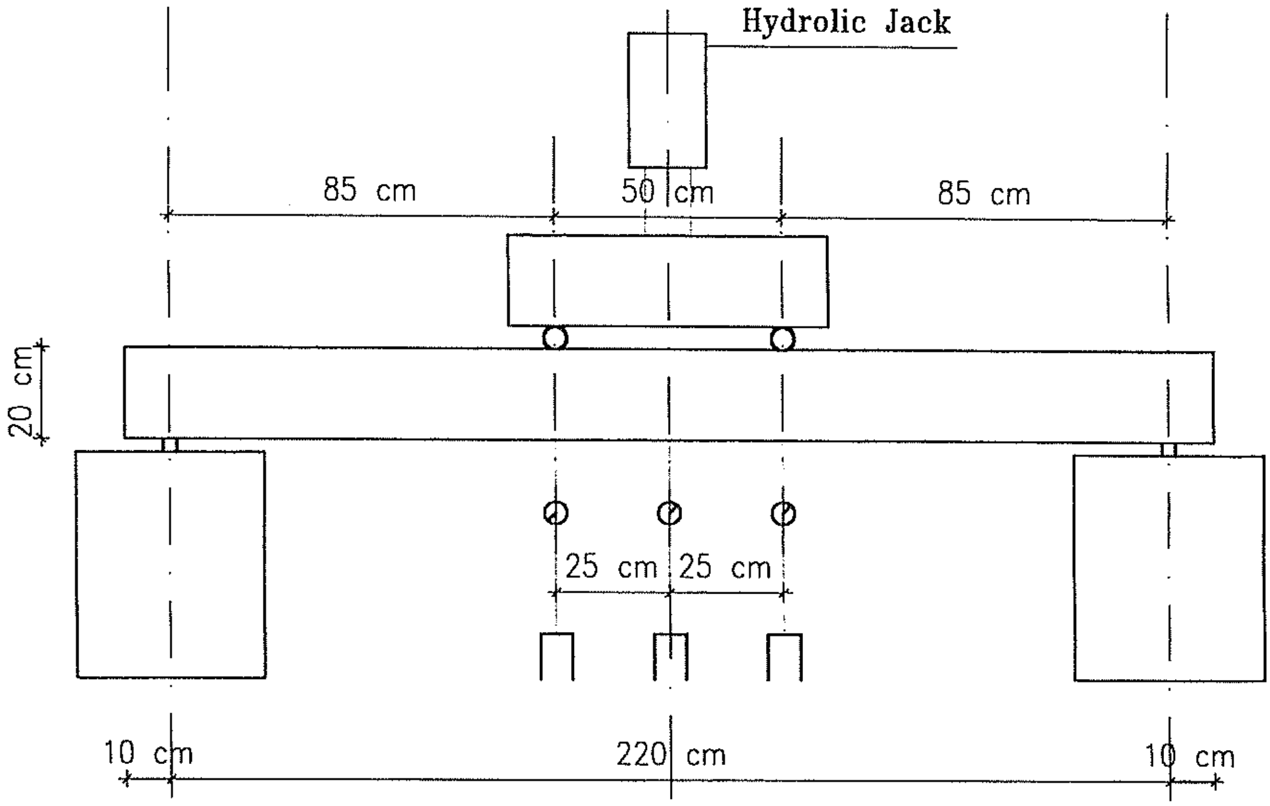

Fig. (2) Test Setup

3-TEST RESULTS AND DISCUSSION

Based on the data available from the tested beams, the following results and discussion could be written.

3-1 Deformation behavior

The load-mid span deflection data of all the tested beams had been recorded. Herein, we plotted some of these data which explain the effect of the studied parameters on load-mid span deflection curves. Fig.(3) showed the effect of number of GFRP layers on the deflection. It is clear from the Fig., that deflection decreased with the increase of number of GFRP layers at the same load.

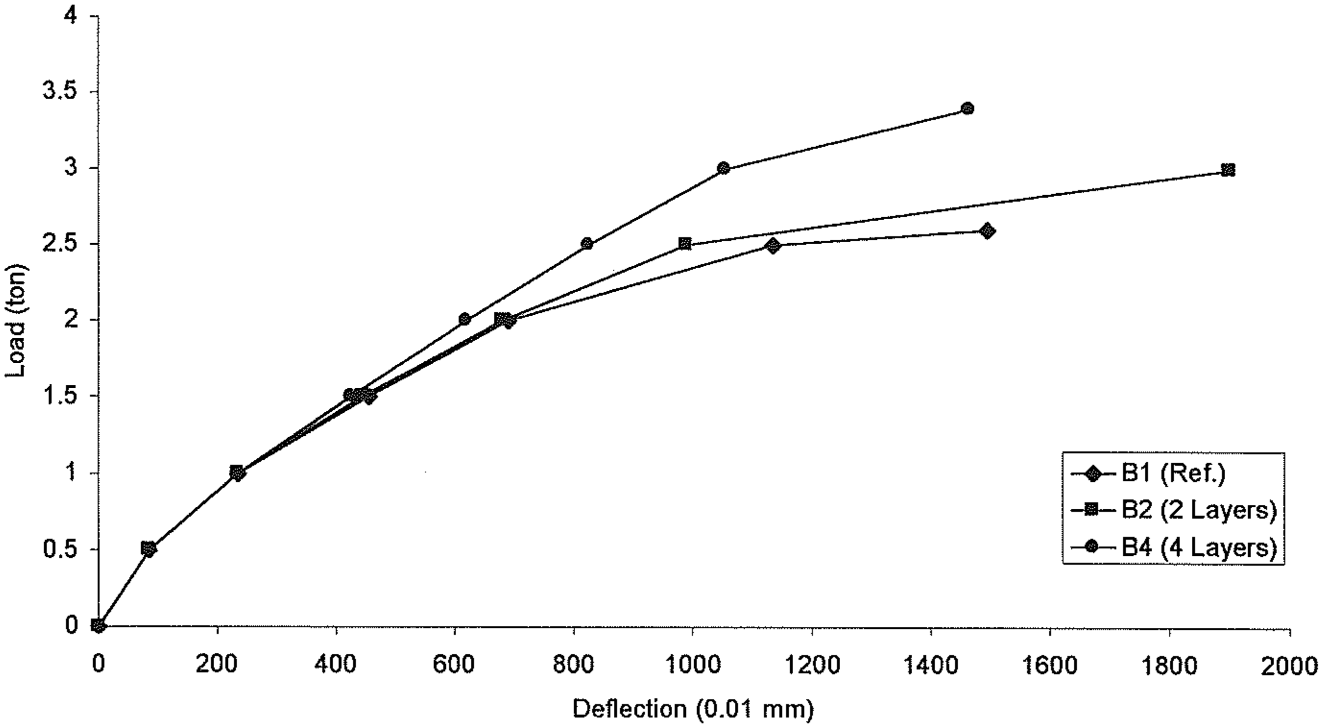

Fig.(3) Load-deflection curves for beams with reinforcement ratio 0.77% at two different strengthening levels

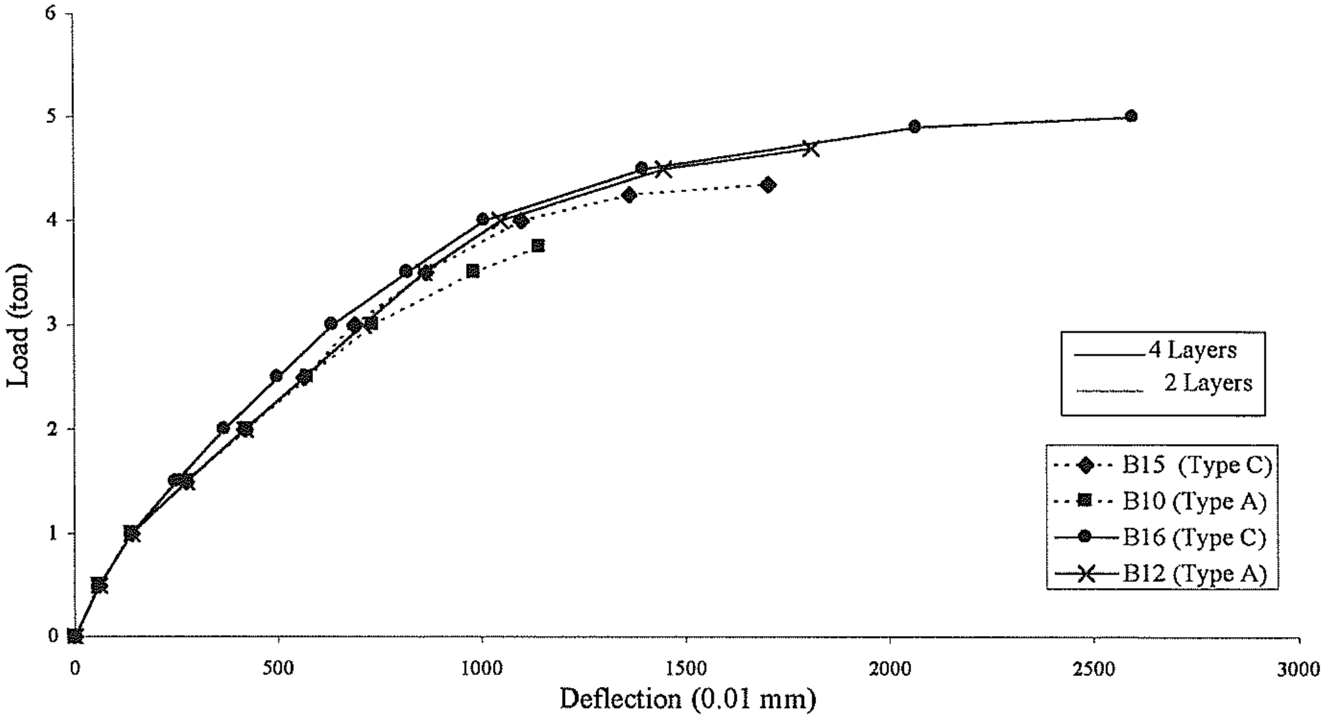

Fig.(4) Load-deflection curves for beams with reinforcement ratio 1.11% at two different strengthening systems

Fig.(4) showed that the system of strengthening by adding GFRP sheets to the tension face with vertical strips (type C) caused a small decrease in the deflection at the same load compared with the same beams strengthened by adding GFRP sheets to the tension face but without the vertical strips (type A).

Fig.(5) confirmed this result and also showed that the strengthening system with confinement strip at the middle zone (type D) caused a noticeable decrease in deflection compared with the two other types (type C and type A). The difference in deflection between the beams strengthened with type A and the similar ones with type B is not noticeable. The preloading of beams up to 0.7 Pu before strengthening causes an increase in deflection mainly due to the permanent deflection after releasing the load before strengthening, and also due to cracking.

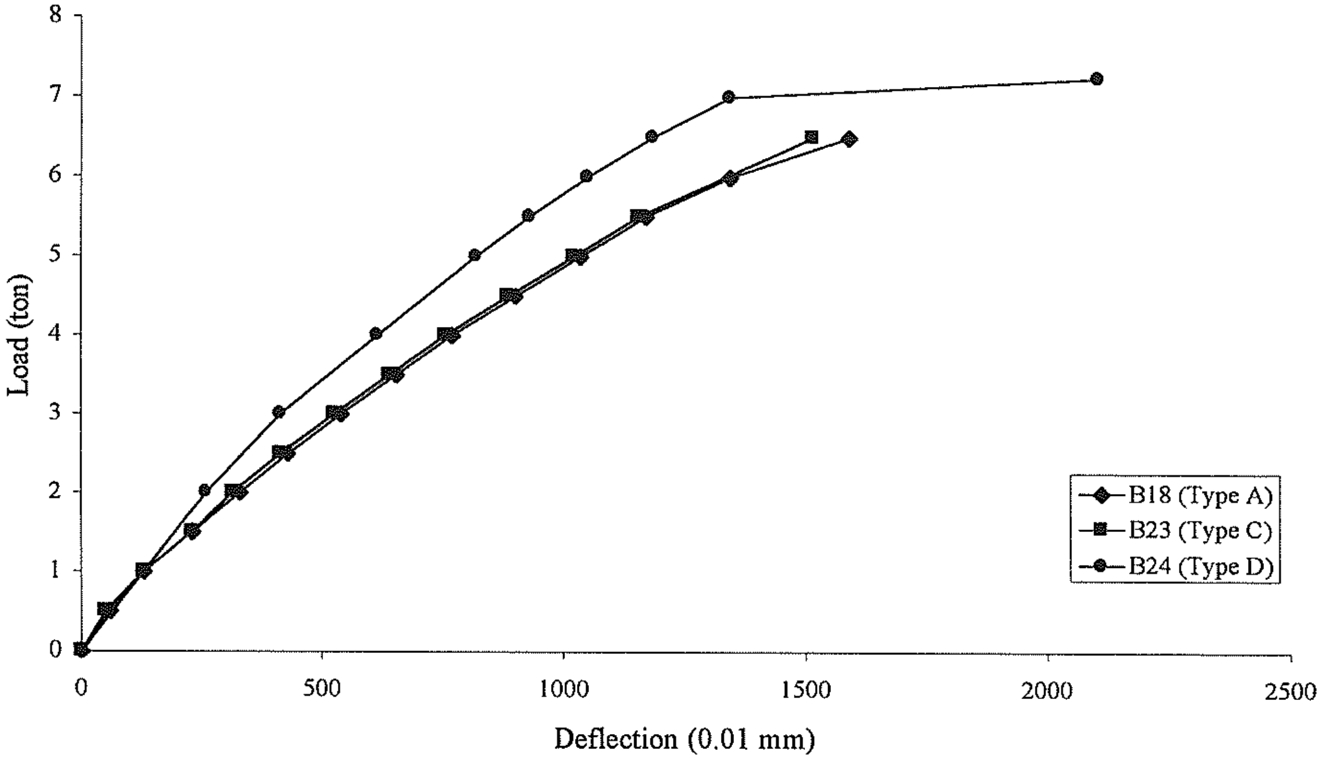

Fig.(5) Load-deflection curves for beams with reinforcement ratio 1.96% with three different strengthening systems

Fig.(6) showed the previous result for beams with reinforcement ratio 0.77% for example. Fig.(6) also showed that the permanent deflection increased with the increase of the preloading i.e. the permanent deflection for beams preloading up to Pu is higher than the similar ones for beams with preloading up to 0.7 Pu . The strain hardening of steel caused a decrease in deflection of beams preloading up to Pu compared with the similar ones at the same load as shown in Fig.(6).

3-2 Ultimate load and mode of failure

The experimental work carried out on the reinforced concrete beams shows three types of failure modes. These modes are:

1) Conventional flexural failure for references beams (unstrengthend beams) which represent in yielding of tension steel, followed by crushing of the concrete, but in our case we didn't continue in loading up to crush the concrete to enable to repair these beams without needing to repair the concrete in the compression zone.

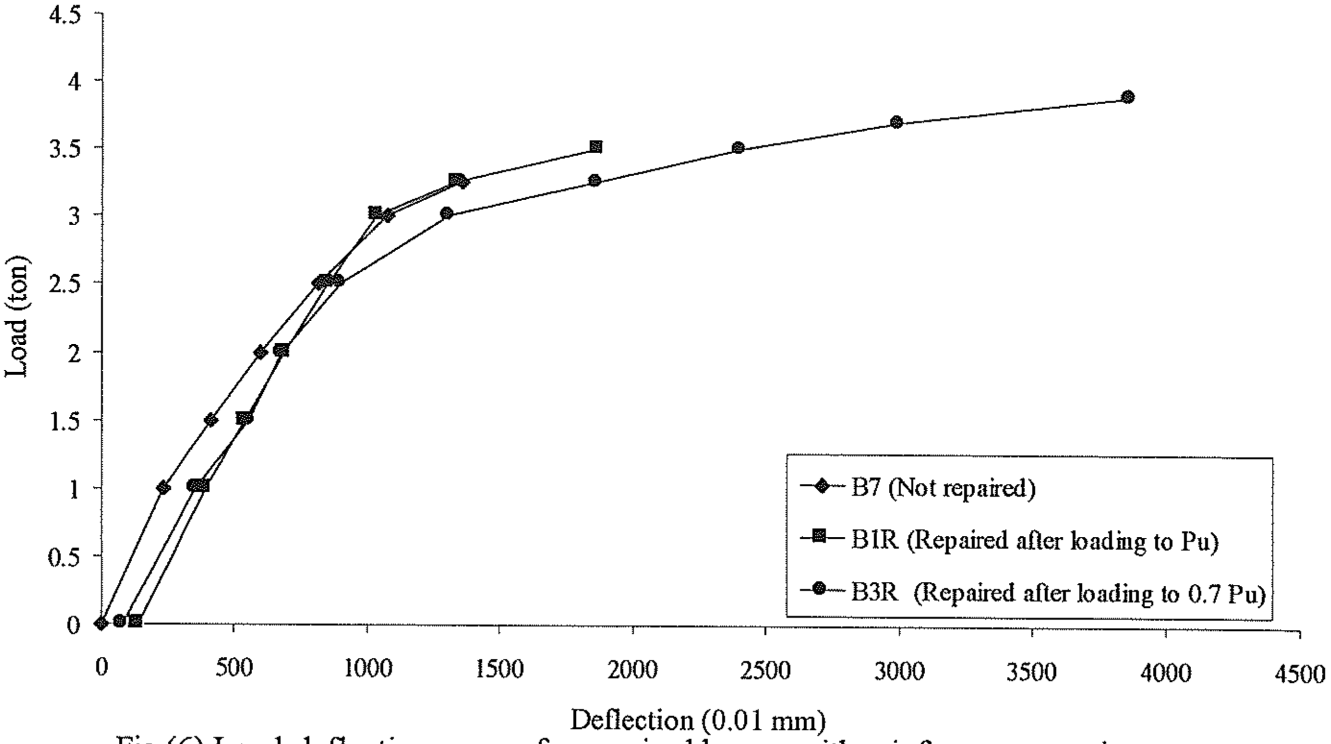

Fig.(6) Load-deflection curves for repaired beams with reinforcement ratio 0.77%

2) Debonding failure , which occurred by debonding of the GFRP sheets that started at the section of maximum moment (under the load) and extended towards the supports when the fiber deformation exceeded. This type of failure was the main one and in some cases when the strengthening system caused a remarkable increase in ultimate load, it followed by crushing of concrete in compression zone.

3) Flexure compression failure, which occurred by concrete crushing in compression zone. This type of failure was mainly in strengthened beams with highest used tension reinforced ratio (ρ=1.96%). In some beams this type of failure followed by debonding of GFRP sheets with the continue of loading. These modes of failure and the ultimate loads of the tested beams are shown in table (2).

The strengthening technique caused an increase in ultimate load reached to 60% higher than reference beam for beams with tension reinforcement ratio (ρ) 0.77%. With the increase of tension reinforcement ratio this excess in ultimate load due to strengthening decreased due to the higher ultimate load of the corresponding reference beam. Also due to the change of made of failure to flexure compression failure with the higher tension reinforcement ratio. The confinement technique used in beam B24 (strengthening system type D) had been made to overcome this type of failure. It succeeded in increasing the ultimate load of this beam to 128% higher than the ultimate load of the corresponding reference beam instead of maximum 110%, which achieved by the other system. The preloading of a tested beams up to 0.7Pu (B3R, B11R, B19R) before repairing caused a small decrease in ultimate load compared with the similar strengthening beams (B7, B15, B23) respectively. The preloading of tested beams up to Pu (B1R, B9R, B17R) before repairing caused unexpected increase in ultimate load compared with the similar strengthening beams (B7, B15, b23) respectively. Studying the experiment data of these beams (B1R, B9R, B17R) showed an excess in yielding load compared with the similar beams. This is attributed to the strain hardening of steel. To confirm this explanation, samples of used steel (ϕ10, ϕ12 and ϕ16) were tensioned in a universal tension machine beyond the yield strength by about 10%, before the load released, then the standard tensile test of the steel had been made. This test showed an increase in steel yielding by about 17%. This result confirmed that the unexpected increase in ultimate loads for the repaired beams (B1R, B9R, B17R) was due to the strain hardening.

Table (2) experimental ultimate load and failure type

Beam No.	Pu exp. (Ton)	$\frac{\text{Pu exp.}}{\text{Pu ref.}}$	Type of failure
B1	2.6	1.0	Steel yielding
B1R	4.15	1.6	Debonding failure
B2	3.2	1.23	Debonding failure
B3R	3.9	1.5	Debonding failure
B4	3.5	1.35	Debonding failure
B5	4.1	1.58	Debonding failure
B6	3.95	1.52	Debonding failure
B7	4.15	1.6	Debonding failure +concert crushing
B8	4.15	1.6	Debonding failure +concert crushing
B9	3.75	1.0	Steel yielding
B9R	4.9	1.31	Debonding failure followed by concert crushing
B10	4.25	1.13	Debonding failure
B11R	4.4	1.17	Debonding failure
B12	4.8	1.28	Debonding failure
B13	5.0	1.33	Debonding failure followed by concert crushing
B14	4.4	1.13	Debonding failure
B15	4.6	1.23	Debonding failure followed by concert crushing
B16	5.0	1.33	Debonding failure followed by concert crushing
B17	6.35	1.0	Steel yielding
B17R	7.25	1.14	Flexure comp failure followed by debonding of GFRPS
B18	6.75	1.06	Debonding failure
B19R	6.9	1.09	Flexure comp failure
B20	7.0	1.1	Flexure comp failure followed by debonding of GFRPS
B21	7.0	1.1	Flexure comp failure
B22	6.9	1.09	Flexure comp failure
B23	7.0	1.1	Flexure comp failure
B24	8.15	1.28	Flexure comp failure followed by debonding of GFRPS

Fig. (7) showed the increased ratio of ultimate load due to the increase of number of GFRP layers. The Fig. Showed that the increase of number of layers from two to four caused an increase in ultimate load but with slightly little rate. As mentioned before this rate is higher for beams with smaller tension reinforcement.

Fig. (8) showed an increase in ultimate load ratio with the increase of area of GFRP sheets whatever the method of strengthened for beams with tension reinforcement ratio (ρ=0.77%). The Fig. also showed that the beams strengthened with type C (horizontal sheets with vertical strips) were the heights in ultimate load followed by type B (U shape sheets), and finally type A (just horizontal sheets).

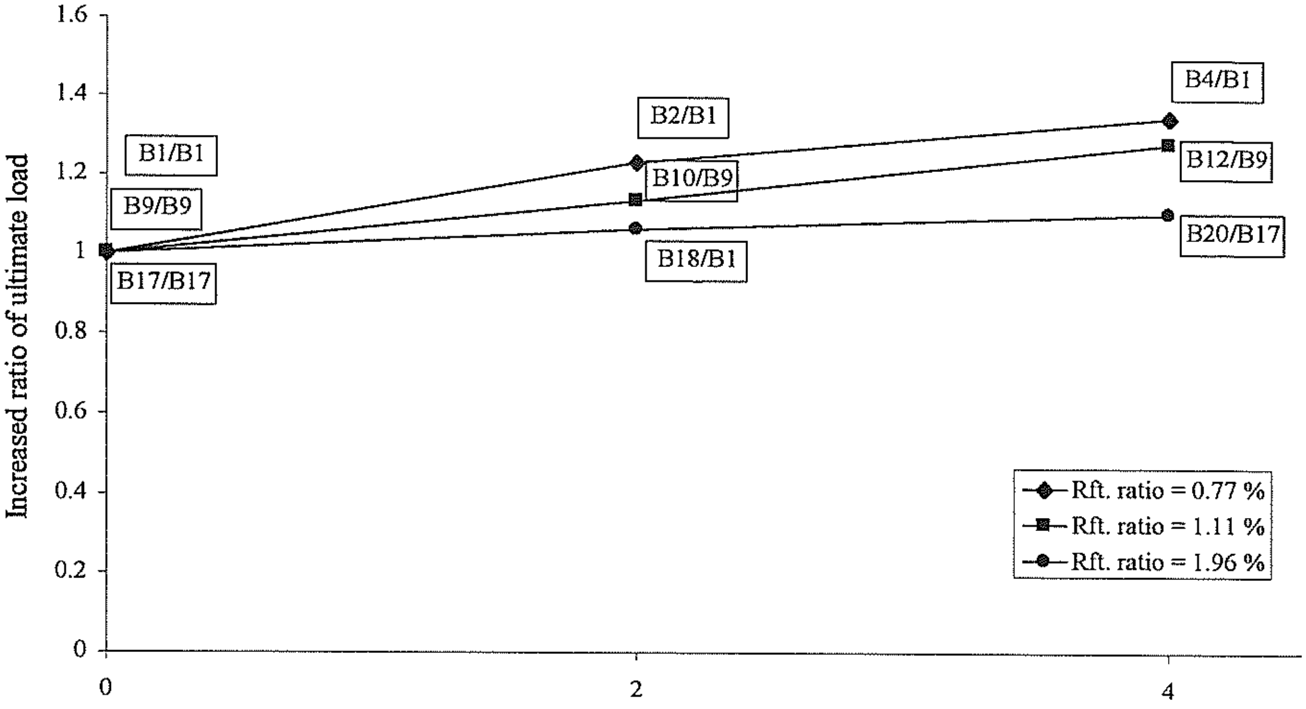

Fig.(7) Increased ratio of ultimate load versus strengthening level at three different reinforcement ratios

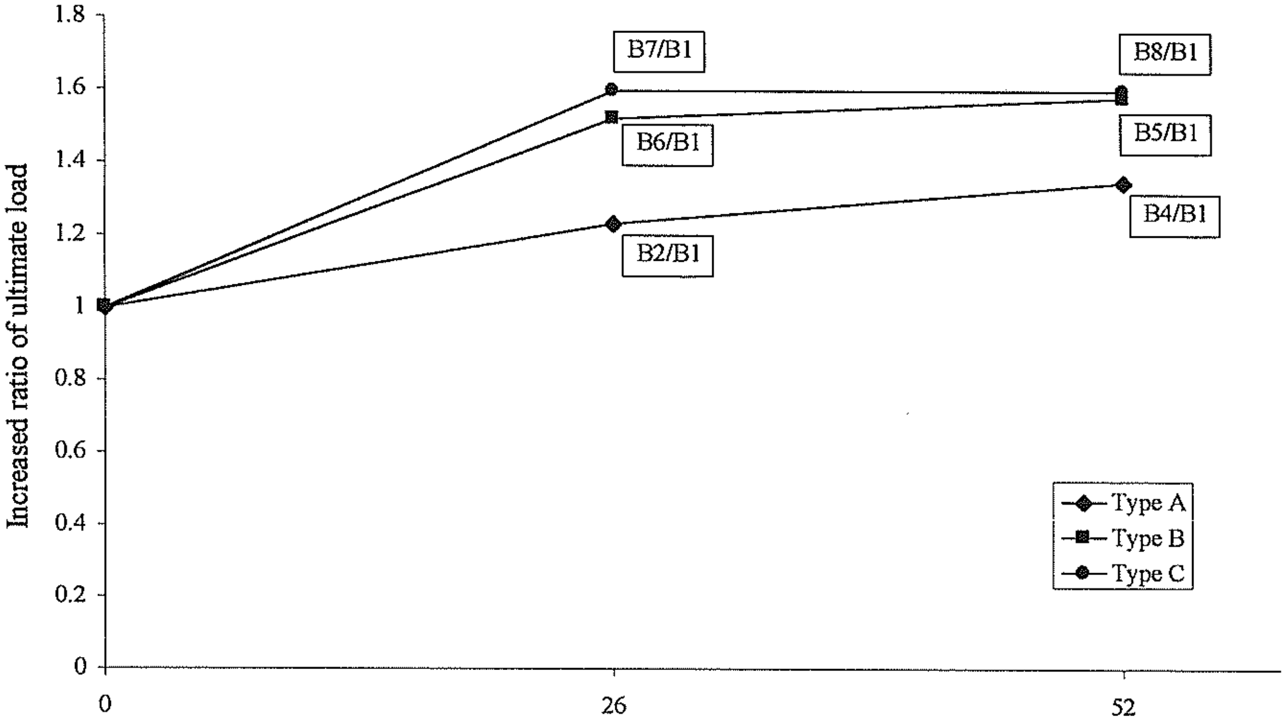

Fig.(8) Increased ratio of ultimate load versus strengthening level for different strengthening systems at reinforcement ratio 0.77%

Fig. (9) showed generally the previous results in Fig. (8) for beams with tension reinforcement ratio (ρ=1.11%).

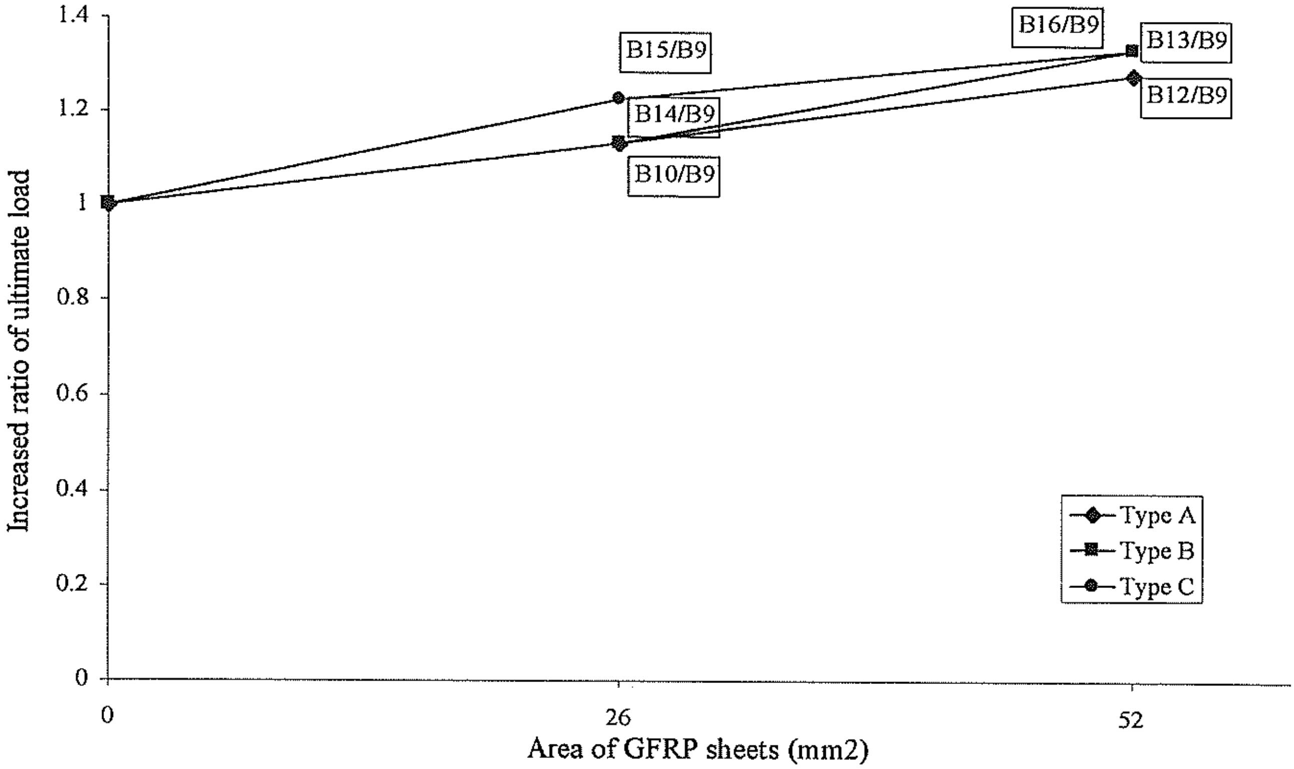

Fig.(9) Increased ratio of ultimate load versus strengthening level for different strengthening systems at reinforcement ratio 1.11%

3-3 Cracking

Fig.(10) showed the crack pattern of some of the tested beams at failure.

Fig.(10) The crack pattern of some of the tested beams at failure

The initial cracking load decreased with the increase of the number of GFRP layers. This is clear by comparing the cracking of beams B4 and B20 (4 layers) with the crackling of beams B2 and B18 (2 layers) respectively. The use of U shape sheets (type B) showed increase in cracking load comparing with the similar beams strengthened by horizontal sheets (type A). This result had been shown by comparing cracking of B5 and B22 with beams B4 and B18 respectively. In beams with vertical strips the cracks extended between these strips see crack pattern of B23. The change of mode failure due to the higher reinforcement ratio and the higher of strengthening level had been shown in crushing of concrete in compression zone as shown in cracking beams B20, B22 and B23. The confinement of this compression zone by wrapping GFRP sheets could raise the compressive resistance of concrete as shown in cracking of B24.

4- THEORETICAL ANALYSIS OF THE STRENGTHENED BEAMS

Based on the assumption that concrete section remains plane after deformation and using the concrete stress block distribution shown in Fig. (11) at ultimate state, from the section equilibrium, the following expression can easily be deduced [11];

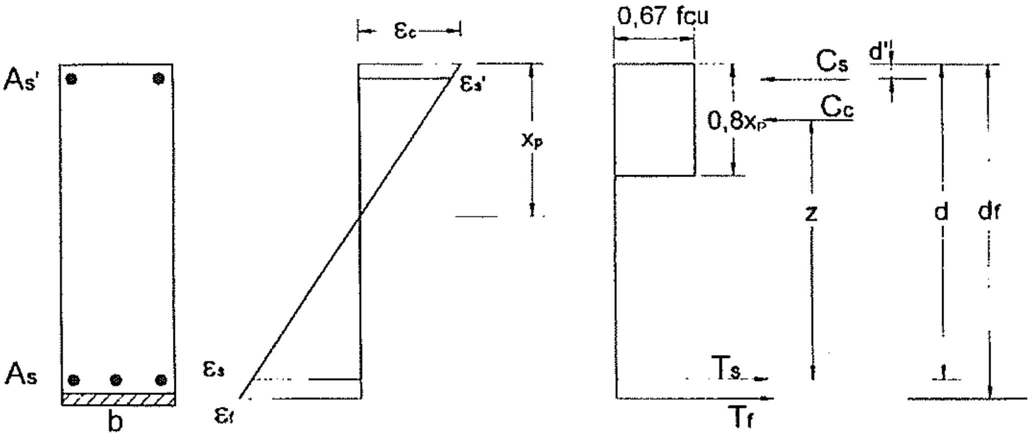

Figure 11 Section strains, stresses and forces at ultimate state.

$$M_u = \sum A_f \sigma_f (d_f - 0.4x_p) + A_s f_y \left(d - 0.4x_p\right) + A_s' \sigma_s' \left(0.4x_p - d'\right) \qquad (1)$$

$$x_p = \frac{A_s f_y - A_s' \sigma_s' + \sum A_f \sigma_f}{0.67 f_{cu}\, 0.8b} \qquad (2)$$

$$\sigma_s' = \varepsilon_s' E_s \qquad (3)$$

$$\varepsilon_s' = \frac{\left(x_p - d'\right)}{x_p} \varepsilon_c \qquad (4)$$

$$\varepsilon_s = \varepsilon_f \frac{\left(d - x_p\right)}{\left(d_f - x_p\right)} \qquad (5)$$

Where A_f = the area of GFRP sheets added to the concrete section ;
A_s = the area of the tension steel ;
A_s' = the area of the compression steel ;
σ_f = the stress in the GFRP ;

d_f = the effective depth of the GFRP ;
x_p = the plastic neutral axis depth ;
f_y = yield of the tension steel ;
$\sigma_s`$ = stress of the compression steel ;
f_{cu} = concrete cube compressive strength ;
$\epsilon_s`$ = strain of the compression steel ;
ϵ_s = strain of the tension steel ;
ϵ_c = maximum compression strain of concrete ;
E_s = modulus of elasticity of steel ;
ϵ_f = strain of the GFRP ;

The GFRP sheets contribution to the beam flexural strength (σ_f) in equation (1) is then determined from the lesser of the following limits:

a- From the limit of $\epsilon_f \leq 0.01$ [in ref (11) this limit was 0.005 where CFRP laminate had been used]

$$\sigma_f = \epsilon_f \cdot E_f = 0.01\ E_f \qquad (6\text{-a})$$

b- From the limit of $\tau = 2$ kg/cm2 referring to the shear stress between the concrete and the GFRP sheets in the shear zone [in ref(11) this limit was τ=0.3Ft referring to the shear stress at the concrete cover associated with tearing off mode failure].

$$\sigma_f = (\tau . L_f . b_f) / (e_f . b_f) = (\tau . L_f) / (e_f) \qquad (6\text{-b})$$

Where E_f = modulus of elasticity of the GFRP.
L_f = shear span, length in which shear stresses are transmitted between GFRP sheets and concrete.
b_f = width of GFRP.
e_f = thickness of GFRP.

Table (3) showed the calculated flexural strength according to the limits of equation (6) (this limits based on the test results of this work). The comparison between the experimental ultimate flexural moment (actual moment ($M_{act.}$)) with the calculated moment (theoretical moment ($M_{th.}$)) showed good agreement. The higher of experimental ultimate moment for the repaired beams B1R, B9R and B17R than the calculated moment is due to the effect of strain hardening which explained before.

5- CONCLUSIONS

Based on the experimental results, the following conclusion can be made:

1- Strengthening of reinforced concrete beams in flexure by the use of external glass fiber reinforced plastic GFRP sheets adhered to the concrete by polyester adhesive is an efficient method of increasing the ultimate load of these beams.

Table (3) calculated flexural strength of the tested beams

Beam No.	fcu(t/cm2)	Mth(t.cm)	Mac(t.cm)	Mac/Mth
B1	0.346	110.534	110.500	1.000
B1R	0.346	143.119	176.375	1.232
B2	0.360	140.259	136.000	0.970
B3	0.390	144.002	165.750	1.151
B4	0.305	139.123	148.750	1.069
B5	0.346	169.035	174.250	1.031
B6	0.345	143.098	167.875	1.173
B7	0.310	142.356	176.375	1.239
B8	0.320	146.727	176.375	1.202
B9	0.305	157.669	159.375	1.011
B9R	0.305	188.908	208.250	1.102
B10	0.305	185.938	180.625	0.971
B11	0.360	190.749	187.000	0.980
B12	0.305	185.938	204.000	1.097
B13	0.380	216.307	212.500	0.982
B14	0.390	191.647	187.000	0.976
B15	0.320	189.439	195.500	1.032
B16	0.360	194.756	212.500	1.091
B17	0.310	268.670	269.875	1.004
B17R	0.310	292.488	308.125	1.053
B18	0.355	296.590	286.875	0.967
B19	0.356	299.108	293.250	0.980
B20	0.342	294.920	297.500	1.009
B21	0.315	310.981	297.500	0.957
B22	0.305	291.606	293.250	1.006
B23	0.354	298.853	297.500	0.995
B24	0.365	303.421	346.375	1.142

2- The strengthening by GFRP sheets increased the ratio of the ultimate load of reinforced concrete beams to the ultimate load of the similar reference beams up to 160%, 133% and 110% for beams with tension reinforcement ratio 0.77%, 1.11% and 1.96% respectively.

3- The tested beams showed three modes of failure, the first was the conventional flexural failure for reference beams (unstrergthend beams), the second was the main one which showed debonding of the GFRP sheets, and the third was flexure compression failure which occurred in beam with higher tension reinforcement ratio ($\rho = 1.96\%$).

4- The confinement of the compression zone in concrete by wrapping it by GFRP sheets (type D) may increase the ratio of the ultimate load of R.C. beams with $\rho = 1.96\%$ to the ultimate load of the similar reference beam up to 128%.

5- The type of the strengthening method affects the efficiency of strengthening. Type C (horizontal GFRP sheets with vertical strips) gave the highest increase in ultimate load followed by type B (U shape GFRP sheets), and finally type A (just horizontal GFRP sheets). This is mainly due to the increase in bonding area.

6- The preloading of some beams up to 0.7 Pu before strengthening (repairing) caused a small decrease in the increase of the ultimate load due to repairing, while the preloading of some beams up to Pu caused a strain hardening of tension steel increasing the ultimate capacity of these beams.

7- The strengthening of R.C. beams by GFRP sheets increased the stiffness of these beams and hence affected its load deflection curves. The number of GFRP layers or its area and the type of the strengthening method affected also the stiffness of these beams.

8- The cracking load increased by adding GFRP sheets, and by increasing the number of layers or the area of these sheets.

9- The application of the GFRP sheets to the beam sides (U shape) delayed the appearance of cracks on these sides.

10- The calculated strengths of the beams showed a good agreement with the test results.

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