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Strengthening reinforced concrete beams using prestressed glass fiber-reinforced polymer–Part I: Experimental study

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Abstract: This work is aimed at studying the strengthening of reinforced concrete (R. C.) beams using prestressed glass fiber-reinforced polymer (PGFRP). Carbon fiber-reinforced polymer (CFRP) has recently become popular for use as repair or rehabilitation material for deteriorated R. C. structures, but because CFRP material is very stiff, the difference in CFRP sheet and concrete material properties is not favorable for transferring the prestress from CFRP sheets to R. C. members. Glass fiber-reinforced polymer (GFRP) sheets with Modulus of Elasticity quite close to that of concrete was chosen in this study. The load-carrying capacities (ultimate loads) and the deflections of strengthened R. C. beams using GFRP and PGFRP sheets were tested and compared. T- and ⊥-shaped beams were used as the under-strengthened and over-strengthened beams. The GFRP sheets were prestressed to one-half their tensile capacities before being bonded to the T- and ⊥-shaped R. C. beams. The prestressed tension in the PGFRP sheets caused cambers in the R. C. beams without cracks on the tensile faces. The PGFRP sheets also enhanced the load-carrying capacity. The test results indicated that T-shaped beams with GFRP sheets increased in load-carrying capacity by 55% while the same beams with PGFRP sheets could increase load-carrying capacity by 100%. The ⊥-shaped beams with GFRP sheets could increase load-carrying capacity by 97% while the same beams with PGFRP sheets could increase the loading-carrying capacity by 117%. Under the same external loads, beams with GFRP sheets underwent larger deflections than beams with PGFRP sheets. While GFRP sheets strengthen R. C. beams, PGFRP sheets decrease the beams' ductility, especially for the over-strengthened beams (⊥-shaped beams).

Key words: Strengthening, Prestressed glass fiber reinforcement polymer, Modulus of Elasticity, R. C. beams
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INTRODUCTION

The aging or deterioration of existing R. C. (reinforced concrete) or P. C. (prestressed concrete) structures is one of the major problems that modern engineers have to face. If the flexural or shear strength of R. C. or P. C. structures is not sufficient to maintain their service functions, strengthening of these structures becomes necessary. To date, steel plates have been used to strengthen concrete members. Using composite plates to strengthen R.C. or P.C. structures offers an exciting alternative because they provide remarkable reductions in weight and are much easier to handle on site. Composite material use in the rehabilitation of R. C. or P. C. structures has received considerable attention in recent years. Books written by Iyer and Sen (1991); Neal and Labossiere (1992); Mufti *et al*.(1991); Nanni (1993); Hollaway and Leeming (1999), have been published on this subject. The advantages and disadvantages in using composite plates instead of steel plates have been studied and discussed in papers written by Saadatmanesh and Ehsani (1991); Meier *et al*.(1992); and Meier (2001). Carbon fiber-reinforced polymer (CFRP) is considered an alternative material for use in strengthening or repairing existing R. C. beams. The American Concrete Institute (ACI) Committee 440 (1996; 2002) and Japan Society of Civil Engineers (JSCE, 1997) published suggestions and regulations on this issue.

Since non-prestressed FRP sheets support only the additional live loads applied to a structure and cannot support existing dead loads, the strengthened or rehabilitated beam may violate the deflection requirements. In other words, beams strengthening with FRP sheets cannot deal with the existing deflections caused by the dead load. With addition to live loads, the total deflection may be too large. The prestressed plates will cause a camber after the prestress is transferred to the R. C. members. This phenomenon will help solve the deflection problem. In some cases the camber can give the beams larger load-carrying capacities.

Limited research on concrete girders strengthened with epoxy-bonded prestressed FRP sheets or plates had been reported. In nearly all these studies, carbon fiber-reinforced polymer (CFRP) was used as the prestressed material. Saadatmanesh and Ehsani (1991) were the first to use prestress-like GFRP sheets. They prestressed the beams by cambering them upward using an upside down load and then bonding the plates to the beam tension faces. Triantafillou *et al.*(1992); Garden *et al.*(1998); Wu *et al.*(1999); Huang *et al.*(2000); and Ferrier *et al.*(2001) used a different process to induce prestress in which the FRP plate ends were tensioned by jacking against an external reaction steel frame independent of the strengthened beams. This study used the same method to prestress the beams. Other researchers (Izumo *et al.*, 1997; Saeki *et al.*, 1997; Andra *et al.*, 1999; Wight and Erki, 2001) strengthened concrete beams with prestressed CFRP sheets directly tensioned by jacking and reacting against the concrete beam itself.

In the literature, nearly all of the researches used CRRP sheets as the prestressing material to strengthen R. C. structures. As indicated in Table 1, the Modulus of Elasticity of CFRP, GFRP sheets and concrete are around 144, 23 and 20.4 GPa, respectively. The Modulus of Elasticity of CFRP sheets is about 7 times that of concrete. The Modulus of Elasticity of GFRP sheets is quite similar to that of concrete. The more similar the Modulus of Elasticity between the two materials, the more prestress will be transferred from one material to the other and the more compatible the structural behavior of the two materials. Because the prestressed FRP sheets are directly bonded to the concrete, the more compatible the structural behavior of the two materials, the fewer negative effects produced, such as residual strain, stress concentration, or cracks etc. Triantafillou *et al.*(1992) reported that concrete bonded beam using prestressed carbon sheet was torn off at both ends when the tension in the FRP sheet was transferred to the concrete. Moreover, the very stiff CFRP sheets cannot cause a significant camber in a repaired beam because the deformation in the CFRP sheet is very small and therefore cannot transfer prestress into the concrete. Therefore, using prestressed GFRP sheets to retrofit damaged beams is a better choice than using prestressed CFRP sheets. Further, because glass fiber is less expensive than carbon fiber, using GFRP sheets as the prestressed material for extensive repairing work can save a large amount of cost. Therefore, using prestressed GFRP sheets can also be a better choice from the economical aspect.

It should be noted that this study did not consider the effect of stress corrosion on the prestressing of GFRP sheets. A high-stress-level prestressed GFRP sheet in a severely wet, alkali and salty environment is very possible to have stress corrosion failure.

The major object of this study is using prestressed GFRP sheets to strengthen reinforced concrete structures. There are two articles included in this study. This article, Part I, is about the experimental study. The accompanying article, Part II discusses the analytical study.

EXPERIMENTAL PROGRAM

Table 1 Properties of carbon fiber, glass fiber, steel and concrete

	Carbon fiber*	Glass fiber*	FRP sheet (with 60% fiber and 40% resin in volume)		Steel	Concrete
			CFRP*	GFRP*		
Strength (MPa)**	3400	3100	1480	460	460	28 (compressive strength)
Modulus of Elasticity (GPa)	230	74	144	23	204	20.4

*Data is provided by the manufacturer, Mitsubishi, Japan; **It is tensile strength if not mentioned

Material properties

Glass fiber was used as strengthening material throughout all the tests in this study. The glass fiber and carbon fiber properties (all of the data are provided by manufacturers) are shown in Table 1 showing that the Modulus of Elasticity of the GFRP sheets is very similar to that of concrete and the glass fiber strength is similar to that of carbon fiber.

Concrete beams

T-shaped and ⊥-shaped concrete beams were used in the experiments in this study. The T-shaped beams are considered under-strengthened beams. This means that all beams, whether reference beams or beams strengthened using FRP sheets, will fail on the tension faces (bottom faces). The ⊥-shaped beams are considered over-strengthened beams. This means that the reference specimens will fail on the tension faces, while the beams strengthened using FRP sheets will fail on the compression faces (top faces). Each type of test regime includes a reference beam, beams strengthened using GFRP sheets and a beam strengthened using PGFRP sheets. The specimen and test procedure details are described below.

1. T-shaped concrete beams

The detailed information on T-shaped concrete beams is listed as follows and schematically shown in Fig.1.

b_f=20 cm; b_w=6 cm; h=25 cm; A_s: 1-#3 steel bar; A_s': 3-#3 steel bars; f_c' =29.1 Mpa; length of beams =200 cm; f_y=358 MPa; stirrups: #3@10 cm.

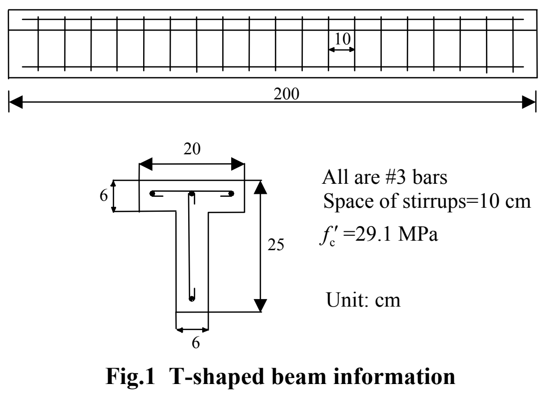

Fig.1 T-shaped beam information

The following is the nomenclature for the T-shaped beams in various bonding types with FRP sheets. These beams are also schematically shown in Fig.2.

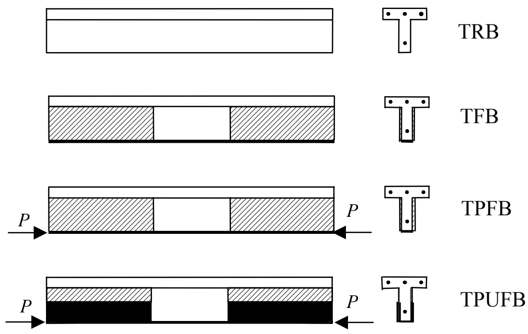

Fig.2 T-shaped beam specimens

TRB: T-shaped reference beam; TFB: T-shaped beam strengthened using one layer of GFRP sheet on the bottom face and one layer of GFRP sheet on each web side of the beam. The GFRP sheets on the web sides are used for shear strengthening; TPFB: T-shaped beam strengthened using one layer of PGFRP sheet on the bottom face and one layer of GFRP sheet on each web side of the beam; TPUFB: T-shaped beam strengthened using one layer of U-shaped PGFRP sheet on the bottom face and one layer of GFRP sheet on each web side of the beam.

2. ⊥-shaped concrete beams

All the ⊥-shaped beam information, as shown in Fig.3, are the same as that for the T-shaped beams. The following is the nomenclature for ⊥-shaped beams in various bonding types with FRP sheets. These beams are schematically shown in Fig.4.

⊥RB: ⊥-shaped reference beam; ⊥FB: ⊥-shaped beam strengthened using one layer of U-shaped GFRP sheet on the bottom; ⊥PFB: ⊥-shaped beam strengthened using one layer of PGFRP sheet on the bottom along with one layer of GFRP sheet on each web side.

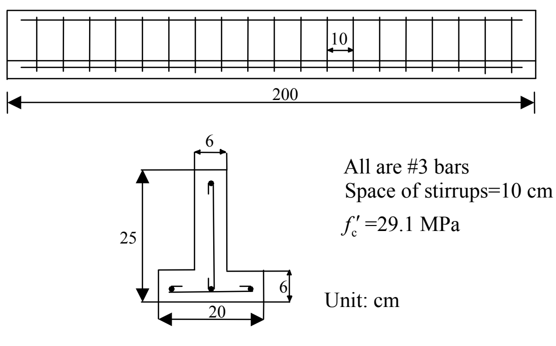

Fig.3 ⊥-shaped beam information

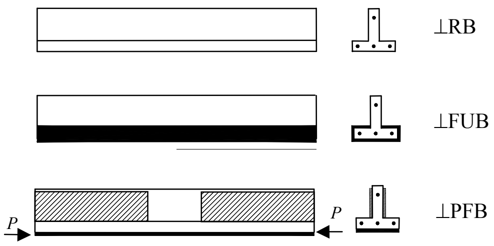

Fig.4 ⊥-shaped beam specimens

Prestressing GFRP sheets and transferring the prestress to the R. C. beams

1. Prestressing equipment

The equipment used to prestress GFRP sheets is shown in Fig.5. As can be seen in this photo, there is a platform on which the GFRP sheets and R. C. beams can be placed. Two clamps, designed to clip the fiber sheets, are installed at both ends of the platform. A jack with a hydraulic pump system is connected to the clamps. Both prestressing and curing processes are conducted using this equipment.

Fig.5 Prestressing equipment

2. Prestressing process

It was suggested that the GFRP sheets were prestressed to half their capacities and that the remaining half capacity was left for resisting future applied loads. Take Beam TPFB for an example, the prestressing process is illustrated as follows:

(1) A glass fiber sheet was placed onto the prestressing equipment platform and both ends of the sheet were clipped with the clamps.

(2) The glass fiber sheet was tensioned until it reached one half of its ultimate strength. For example, for Beam TPFB, the tension loading was 179400 N [i.e. 0.13 (thickness)×60 (width)×46000/2].

(3) After the GFRP sheet was tensioned, the epoxy matrix was brushed onto the GFRP sheet until it was fully impregnated.

(4) The R. C. beam followed a standard procedure to ensure a well prepared surface of concrete for bonding.

a. A grinding wheel was used to prepare the concrete surface for bonding; care was taken to expose the coarse aggregates.

b. An air-compressor nozzle was use to clean the ash and debris from the ground surface.

c. For rectangular shape beams, the sharp corners were ground into round corners with a radius greater than 2 cm.

d. Any hole or cave on concrete surface was filled with resin mortar and then ground smooth.

e. The base matrix was brush onto the concrete surface to receive the GFRP sheet. After the base matrix had polymerized, a final check was made to ensure the concrete surface was smooth.

(5) The concrete beam was placed onto the tensioned GFRP sheet, which had been fully wetted. C-shaped clips were used to tighten the GFRP sheet and the beam together.

(6) The curing process for the specimen (shown in Fig.6) was sustained for more than three days.

Fig.6 Curing process

(7) The GFRP sheet was cut from the clamps.

The GFRP sheets were cut so that the prestressed beam could be moved away from the prestressing equipment. The polymerized epoxy between the concrete and GFRP sheet will transfer the pretension from the GFRP sheet to the R. C. beam and cause a small camber to be formed on the beam's upper surface.

Bending tests for R. C. beams

All of the reference beams, beams strengthened using GFRP sheets and the beams strengthened using PGFRP sheets, were tested using the bending test set-up shown in Fig.7. The beams were simply supported beams. Three LVDTs were placed at the middle and two one-third points under the beams. The loads were applied at the two one-third points on the beams. All of the bending tests followed the displacement control principle. The loads were applied until the specimens failed.

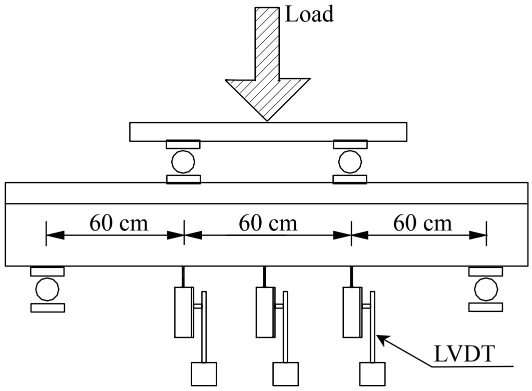

Fig.7 Arrangement for bending tests

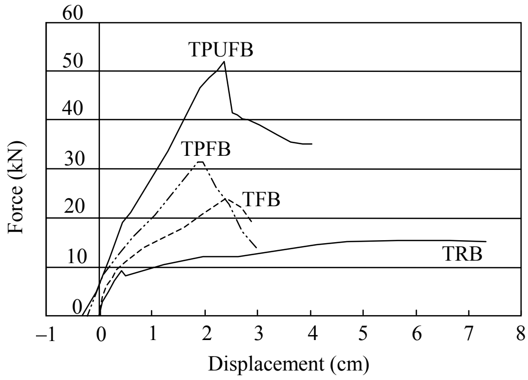

Fig.8 Test results for T-shaped beams

Concrete crack and FRP sheet spalling on the bottom

Fig.9 Failure on the bottom of Beam TFB

Concrete crack and PGFRP sheet spalling on the bottom

Fig.10 Failure on the bottom of Beam TPFB

Test results and discussions

1. T-shaped beams

The test results for the T-shaped beams are shown in Tables 2 and 3 and Fig.8. Table 2 indicates that using GFRP sheets to strengthen R. C. beams can increase their first-crack loads and ultimate loads. The test results also showed that all the T-shaped beams were under-strengthened beams, that is, they all failed on the tension face (the bottom face), as shown in Figs.9 and 10. Therefore, the strengthening effects of different bonding types can be directly compared. Table 2 lists the first-crack load and ultimate load occurrence. Beam TPUFB had the largest first-crack load of 11 kN, Beam TPFB had 8 kN, Beam TFB had 7 kN and Beam TRB had the smallest one of 4 kN. The test results showed that the GFRP sheets had apparent effect in enhancing the first-crack loads. Also, the GFRP sheets had an apparent effect on the beams' ultimate loads. The test results also showed that if the PGFRP sheet is U-shaped, like Beam TPUFB, the enhancement can be even better than that on Beam TPFB.

In Table 3, the R. C. beams cambers caused by PGFRP sheets were 0.285 cm and 0.205 cm for the TPFB and TPFUB beams, respectively. The sum of the camber caused by the PGFRP sheets and the yielding/ultimate deflection in Beam TPFB can be compared with the yielding/ultimate deflection of Beam TFB. This relation is illustrated in the following equations:

Table 2 First-crack loads and ultimate loads for T-shaped beams

Specimens	First-crack loads (kN)	Increase percentage of first-crack loads (%)	Ultimate loads* (kN)	Increase percentage of ultimate loads (%)
TRB	4	0	16.0	0
TFB	7	75	24.8	55.0
TPFB	8	100	32.0	100.0
TPUFB	11	175	52.0	225.0

*The load at that the P-Δ curve begins going down is the ultimate load

Table 3 Deflections and ductilities of T-shaped beams

Specimens	Cambers (cm)	Yield deflections* (cm)	Ultimate deflections** (cm)	Ductility ratios***
TRB		0.334	5.61	16.8
TFB		0.440	2.25	5.11
TPFB	−0.285	0.254	1.92	3.56****
TPUFB	−0.205	0.244	2.38	5.30*****

*Using 0.2 % offset method to determine yielding load and deflection; ** The points at that the P-Δ curves begin going down are the ultimate deflections and loads; ***Ductility ratio=Ultimate deflection/(camber+yield deflection); ****1.92/(0.285+ 0.254)=3.56; *****2.38/(0.205+0.244)=5.3

$[(\text{camber}+\Delta_{\text{yielding}})_{\text{Beam TPFB}}]$ is compared with

$$[(\Delta_{\text{yielding}})_{\text{Beam TFB}}] \tag{1}$$

They are 0.285+0.254=0.539 and 0.44;

and

$[(\text{camber}+\Delta_{\text{ultimate}})_{\text{Beam TPFB}}]$ is compared with

$$[(\Delta_{\text{ultimate}})_{\text{Beam TFB}}] \tag{2}$$

They are 0.285+1.92 =2.205 and 2.25.

The T-shaped beams were under-strengthened beams and always failed on the tensile face whether the fiber sheets were bonded or not. Because the yielding/ultimate strain of the fiber sheets is constant, the sum of the camber and the yielding/ultimate deflection of Beam TPFB should be, in theory, equal to the yielding/ultimate deflection of Beam TFB. According to Eqs.(1) and (2), the deflections compared well.

Table 3 and Fig.8 show that the ductilities of the beams strengthened using GFRP sheets like Beam TFB or using PGFRP sheets like Beam TPFB are smaller than those of the reference beam, Beam TRB. This research result was the same as all previous parallel research results that all strengthened beams will have less ductility. According to Table 3 Beam TPFB had a ductility ratio of 3.56 and Beam TFB had a ductility ratio of 5.11. Both of them are far smaller than the ductility of 16.8 of the reference beam, Beam TRB. This indicates that the prestressed strengthened beams would exhibit less ductile than the regular strengthened beams. On the other hand, Beam TPUFB in which the PGFRP sheet was U-shaped had a ductility ratio of 5.3 which is very similar to Beam TFB's ductility ratio, 5.11. This indicates that Beam TPUFB with a U-shaped PGFRP sheet exhibited better ductile behavior than Beam TPFB in which the PGFRP sheet was bonded only on the beam's bottom face.

In all of the tests, no concrete was torn off when the prestress was transferred from the fiber sheets into the concrete. The test results showed that compared to using GFRP sheets, PGFRP sheets on T-shaped beams gives the beams larger first-crack and ultimate loads. Both fiber sheet types produced similar ductility with no torn-off concrete during stress transfer.

2. ⊥-shaped beams

The test results for the ⊥-shaped beams are shown in Table 4 and Fig.11. According to Table 4, in Beam ⊥FB and Beam ⊥PFB, both of the strengthening effects were over 97%. Because this beams strengthened with FRP sheets are over-strengthened, no cracks will develop on the tension faces when they are subjected to external loads. Therefore, unlike T-shaped beams, no first-crack loads exist for this type of beams. As for the ultimate loads, as shown in Table 4, Beam ⊥RB had 31.5 kN of ultimate load, Beam ⊥FB had 62.2 kN and Beam ⊥PFB had the largest one, 68.5 kN. As for the failure pattern, the failure of Beam ⊥RB occurred on the bottom face (the tension face), as shown in Fig.12. In theory, the concept concrete beam design must make the bottom face (tension face) weaker than the top face (compression face) and leave failure occurring at the tension face to behave nice ductility during failure. A concrete beam will behave like a ductile member if it is designed with this concept in mind. In ⊥-shaped beams with GFRP sheets, the GFRP sheets on the wide bottom faces make the bottom faces stronger than the top faces and prevent failure from occurring on the top faces as shown in Fig.13. Under this situation, the strengthened ⊥-shaped beams become fracture members.

Table 4 Ultimate loads for ⊥-shaped beams

Specimens	Ultimate loads (kN)	Increase percentage of ultimate loads (%)
⊥RB	31.5	0
⊥FB	62.2	97.4
⊥PFB	68.5	117.5

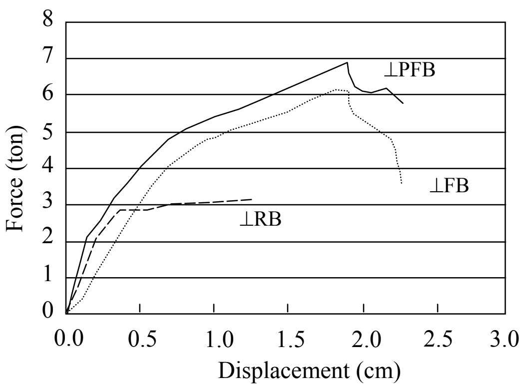

Fig.11 Test results for ⊥-shaped beams

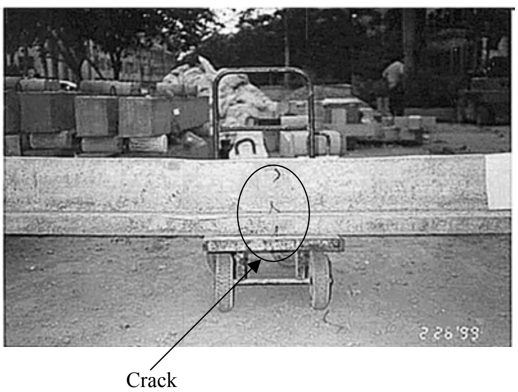

Fig.12 Failure on the bottom of Beam ⊥RB

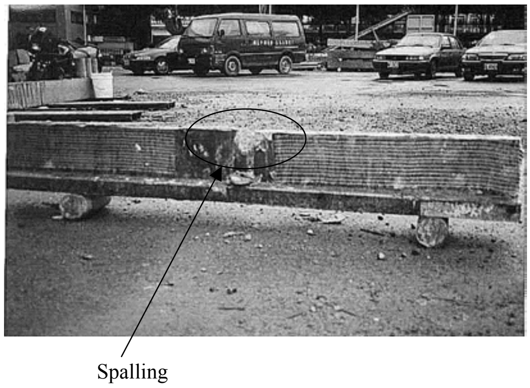

Fig.13 Failure on the top of Beam ⊥FB

Fig.11 shows that the beam strengthened using PGFRP sheets (Beam ⊥PFB) has smaller deflection than the beam strengthened using regular GFRP sheets when the external loads are the same. However, the yielding and ultimate deflection relations shown in Eqs.(1) and (2) did not occur. This is because the failure position has changed from the bottom fiber face to the top concrete face when GFRP/PGFRP sheets are used for strengthening. Therefore, the cambers were not measured for comparisons in all tests for ⊥-shaped beams and the zero deflection was set at the moment when the external load was applied. In Fig.11, the plastic range shown in the P-Δ relation curve for Beam ⊥RB was not recorded. Therefore, the ductility of the reference beam and the beams with GFRP/PGFRP sheets cannot be compared. Comparison of Fig.8 with Fig.11, it is showed that the ductility of the over-strengthened beams (⊥-shaped beams strengthened using GFRP/PGFRP sheets) is worse than that of the under-strengthened beams (T-shaped beams strengthened using GFRP/PGFRP sheets). This is because the fiber sheets in ⊥-shaped beams change the failure modes from the bottom fiber face to the top concrete face. Because concrete is a brittle material, this type of failure makes the ⊥-shaped strengthened beams less ductile than the T-shaped strengthened beams. In conclusion, beams strengthened with FRP sheets have smaller ductility than non-strengthened beams and the over-strengthened beams have even smaller ductility.

No concrete was torn off when the prestress was transferred from the fiber sheets to the concrete. According to the test results, compared with using GFRP sheets, PGFRP sheets in ⊥-shaped beams give the beams capacity to bear larger ultimate loads, have similar ductility and do not tear concrete off during stress transfer.

CONCLUSION

T- and ⊥-shaped R. C. beams were tested in this study. T-shaped beams are considered under-strengthened beams because they always fail on the strengthened face (tension face) before or after strengthening. ⊥-shaped beams are considered over-strengthened beams because they change the failure position from the tension face to the compression face after strengthening. The following conclusions were arrived at from the test results and discussion:

1. Using PGFRP sheets to strengthen R. C. beams does not cause concrete spalling in both over-strengthened and under-strengthened beams.

2. Strengthening beams with GFRP sheets or PGFRP sheets give them the capacity to withstand larger ultimate loads than beams without fiber sheets.

3. For both over-strengthened and under-strengthened beams, the beams with PGFRP sheets can withstand larger ultimate loads than beams with GFRP sheets. However, the over-strengthened beams do not show obvious first-crack loads.

4. The deflections of the beams with PGFRP sheets are smaller than those of beams with GFRP sheets under the same external loads.

5. For under-strengthened beams, the camber summation caused by the PGFRP sheets and yielding or ultimate beam deflections with PGFRP sheets are quite close to the yielding and ultimate deflection of beams with GFRP sheets.

6. Beams with GFRP/PGFRP sheets exhibit ductility values smaller than those of beams without fiber sheets. The ductilities of the over-strengthened beams were especially smaller.

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