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Use of fibers with large fracture strain and low elastic modulus for flexural strengthening of RC beams

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ABSTRACT

Potential application of ductile polyethylene terephthalate (PET) that has high strength and low elastic modulus in flexural strengthening of RC members was investigated both experimentally and analytically. Experimental program consisted of tensile test of 3 different types of fibers (CF, GF, PET) and flexural test of six RC beams externally strengthened using the fibers. Tensile test results revealed that the PET has a nonlinear stress-strain relationship. All RC beams strengthened using PET demonstrated significantly improved moment capacity and ductile load-deflection behaviour. Results of section analyses using nonlinear stress-strain relationship of PET closely matched findings of the experimental part in terms of yield and ultimate moments. Consideration of adhesive mechanical properties in the moment calculations was important to accurately predict the moment capacities of the PET strengthened beams.

Keywords: PET, large fracture strain, low elastic modulus, flexural strengthening, fiber

1. INTRODUCTION

External strengthening using fiber reinforced polymer, such as carbon fiber (CF) and glass fiber (GF), has often been used in Korea to strengthen existing RC columns, beams, and slabs. The RC members strengthened using CF or GF can exhibit brittle mode of failure due to limited strain capacity that is typically on the order of 1~3%. To overcome such disadvantages intrinsic to CF and GF, use of ductile PET which demonstrates about 15% fracture strain was exploited in this study. PET has been used for seismic retrofitting of RC columns in recent years in Japan (Anggawidjaja 2006) utilizing high strength and ductile characteristics, but was seldom used for flexural strengthening due to low modulus of PET that is smaller than 1/20 of steel.

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1) Professor

2. MATERIAL PROPERTIES AND TEST VARIABLES

2.1 Material Properties of Fibers and Adhesive

CF and GF fiber rovings and bi-axially woven PET sheet were used in the experimental program. Table 1 and Fig. 1 summarize the material properties of three different types of fiber and a two-part epoxy determined from coupon test. As can be seen in Fig. 1, the stress-strain relationship of PET is nonlinear. Method of least square was used to determine the best fit model of PET stress-strain relationship up to 4% strain as shown in Fig. 2. In Fig. 2, Model 3 was later used to determine moment-curvature relationship of the PET-strengthened beams.

Table 1 Mechanical properties of fibers and adhesive

Material	Stress (MPa)	Strain (mm/mm)	Elastic modulus (GPa)	Cross section (mm^2)	Thickness (mm)	Density (g/mm^3)
CF roving	1,970	0.0116	169	0.446 1)	0.109	0.00180
GF roving	558	0.0128	44.8	0.970 1)	0.424	0.00254
PET sheet	613	0.1495	7.10 2)	5.250 3)	0.106	0.00140
Adhesive	40.9	0.0258	1.59	--	--	--

Note: 1) Cross-sectional area of a fiber roving; 2) secant modulus corresponding to 1% strain; 3) cross-sectional area of PET sheet per 100-mm width (fibers in the axial direction only)

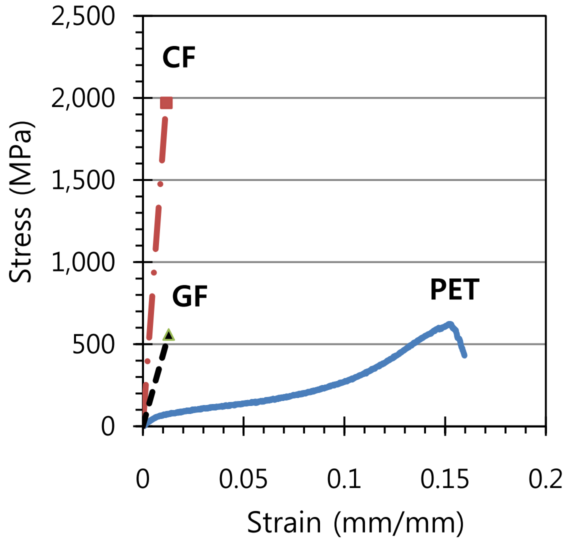


Fig. 1 σ-ε plot of various fibers in tension

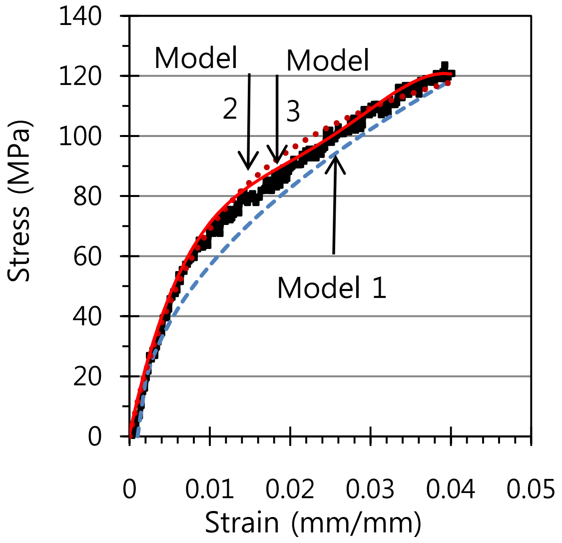


Fig. 2 Curve fitting result: PET σ-ε curve

2.2 Hybridization of Fibers

One potential drawback of PET can be the low elastic modulus. Mixing PET with stiffer CF (CF-PET hybridization) can be a way to overcome this potential drawback so that the RC beams strengthened using hybridized fibers demonstrate increased stiffness under the service load and high ductility at ultimate stage (Choi 2011).

Proper mix proportions between CF and PET were investigated using a theoretical formula proposed by Manders et al. (Manders and Bader 1981) that resulted in a critical ratio of CF:PET = 23:77 by vol. as shown in Fig. 3. Fig. 3 indicates that, when CF quantity is less than 23% of the total fiber volume (CF+PET), PET will be able to further resist the force after rupture of CF in tension.

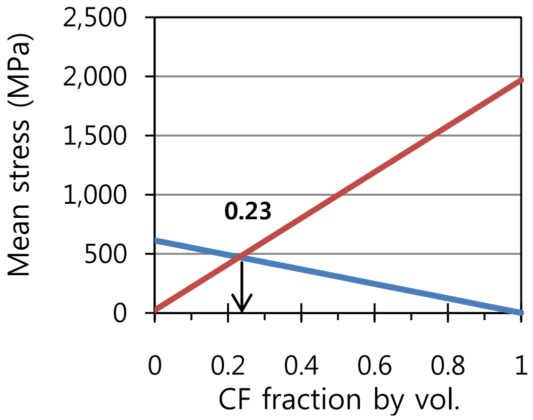


Fig. 3 Fiber mix proportion

Table 2 Variables of RC beam test

Beam index	Fiber type	Fiber cross-sectional area (mm^2)
B-Control	--	--
B-CF	CF	21.0
B-GF	GF	79.5
B-PET	PET	200.0
B-HF-5-95	CF/PET	7.75/147.3
B-HF-10-90	CF/PET	10.5/94.5

2.3 Variables of Beam Tests

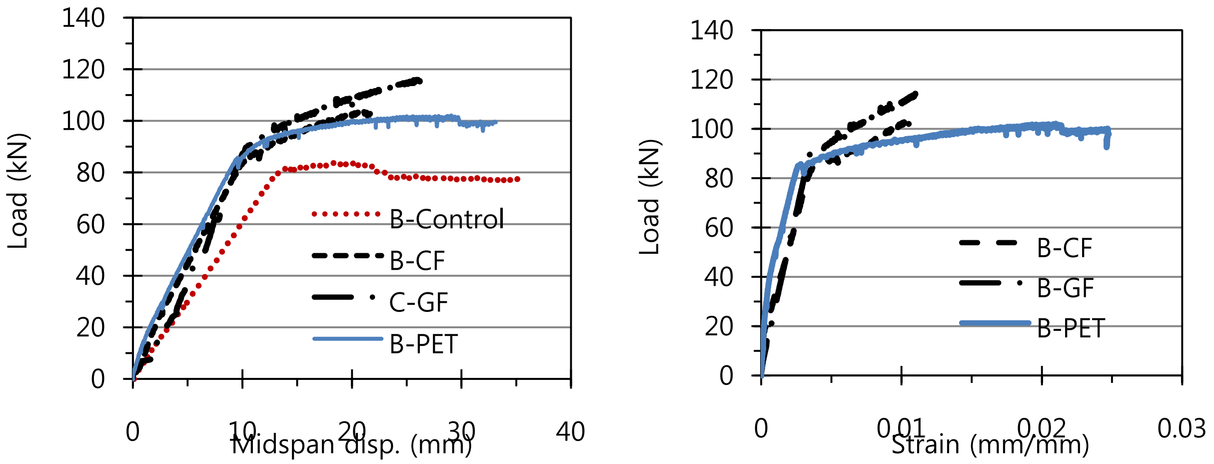
A total of six RC beams was fabricated and tested where Table 2 summarizes the test variables. Beam cross section was 200 mm (b) * 200 mm (h) with an effective depth (d) of 160 mm. Beam reinforcement consisted of 3D13 (tension bars) and 2D10 (compression bars). Stirrups were provided to prevent shear failure. All beams were tested under 4-point loading while the span length was 1.8 m. Yield strength, tensile strength, and elastic modulus of D13 bars were 458 MPa, 590 MPa, and 188 GPa, respectively. Yield strength, tensile strength, and elastic modulus of D10 bars were 486 MPa, 616 MPa, and 195 GPa, respectively. Concrete compressive strength was 24.7 MPa. Fibers were bonded to the concrete substrate using a two-part epoxy where the adhesive amount was 200% of fiber by vol. It needs to be noted that the amount of PET in terms of axial stiffness ($E_{PET}A_{PET}$) is only about 50% of that provided by CF ($E_{CF}A_{CF}$) or GF ($E_{GF}A_{GF}$) in Table 2. The delamination of fibers from concrete substrate was intentionally prevented by using the mechanical anchorage in all beams.

3. TEST RESULTS

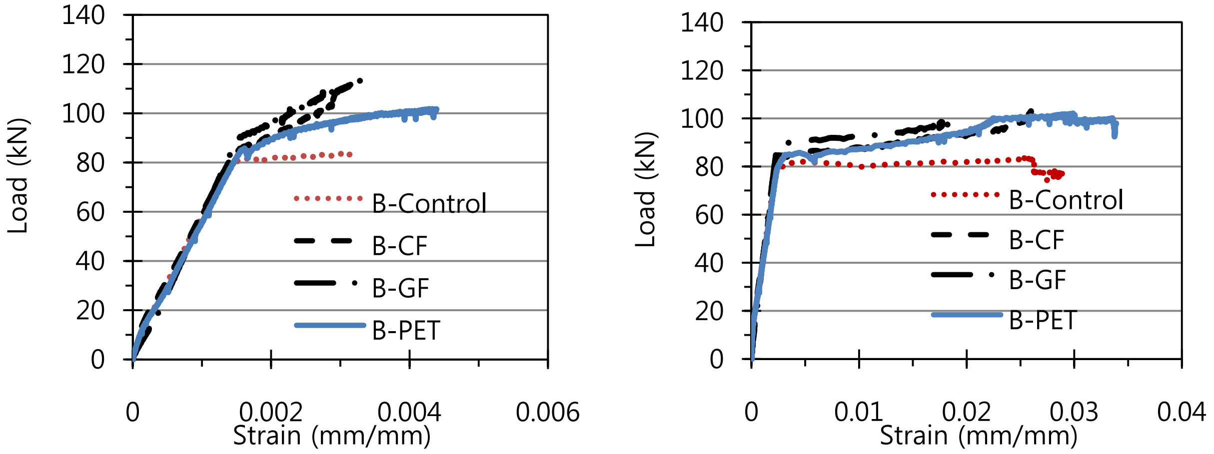
Table 3 is a summary of the beam test results in terms of load, stiffness, and displacement values at yield and ultimate stages, respectively. B-Control is an unstrengthened beam, while B-CF, B-GF, and B-PET are the beams strengthened using CF, GF, and PET, respectively. Hybridized CF-PET fibers were used for the remaining two beams using CF:PET ratios of 5:95 and 10:90 by vol. for the B-HF-5:95 and B-HF-10:90, respectively.

Table 3 Summary of beam test results

Beam index	Yield				Ultimate			Failure mode
	P_y (kN)	Δy (mm)	Stiffness (N/mm)	P_y/P*	P_u (kN)	Δu (mm)	P_u/P*	
B-Control *	77.7	12.8	6,070	--	83.9	35.3	--	flexure
B-CF	84.5	11.7	7,222	1.09	104	21.7	1.24	CF rupture
B-GF	89.3	10.3	8,670	1.15	116	26.6	1.38	GF debonding
B-PET	81.6	9.0	9,067	1.05	102	35.0	1.22	flexure
B-HF-5:95	88.5	11.3	7,832	1.14	108	35.1	1.29	flexure
B-HF-10:90	81.8	12.0	6,817	1.05	107	35.3	1.28	flexure

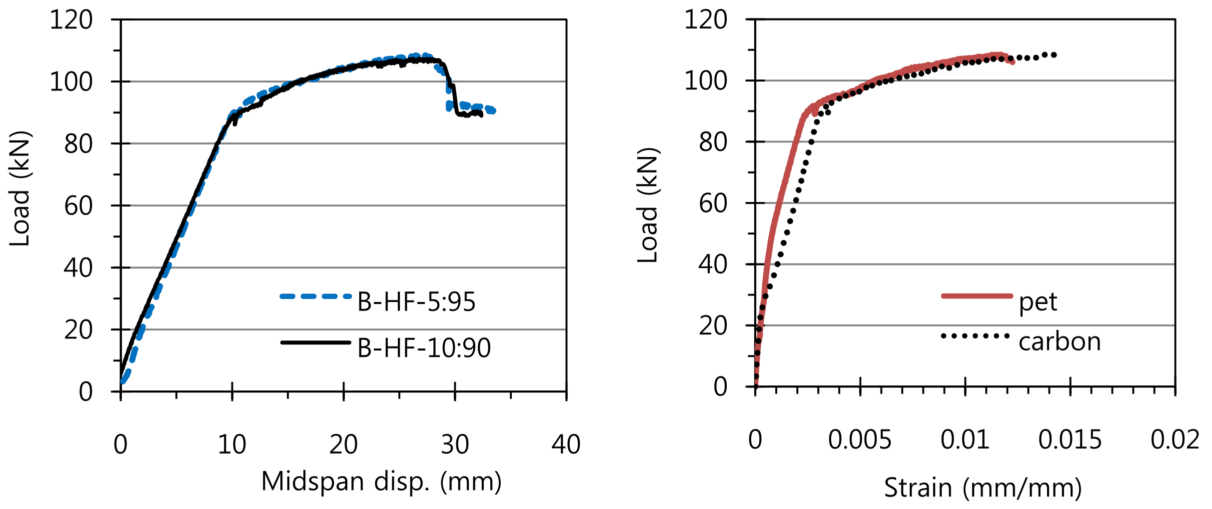


(a) Load vs. midspan displacement (b) Load vs. fiber strain



(c) Load vs. concrete strain (d) Load vs. tension rebar strain

Fig. 4 Test results of control beam and beams strengthened using CF, GF, and PET



(a) Load vs. midspan displacement (b) Load vs. fiber strain : B-HF-5:95

Fig. 5 Test results of beams strengthened using hybridized CF-PET

In Table 3 and Fig. 4(a), initial stiffnesses of the load-displacement plots are greater than that of B-Control while the stiffnesses are similar in all strengthened beams. At ultimate, B-CF failed suddenly as CF ruptured at about 1.1% strain a shown in Fig. 4(a), (b) while B-GF failed by local debonding between GF and concrete near tip of a diagonal crack. B-PET demonstrated a ductile load-deflection behaviour without any fiber rupture or debonding and failed in flexure. It is noted that, for B-PET, the maximum PET strain value reached about 2.5% in Fig. 4(b) which is significantly larger than that of CF and GF. At ultimate, the peak load of B-CF, B-GF, and B-PET increased over B-Control by 20%, 38%, 22%, respectively. The effect of fiber strengthening was more pronounced at ultimate stage than at the yield stage. This is true especially for the PET, probably because the PET has low elastic modulus and it takes large strains to develop for the PET to become more effective.

Fig. 5(a) shows that, after rupture of CF at peak, PET help continue to resist load as it is demonstrated by the level of load about 90 kN which is higher than 83.9 kN (peak load of B-Control). Probably due to lack of ductility of the beam section, the effect of hybridization of fibers is not pronounced.

4. SECTION ANALISES

Section analyses followed the experimental work to:

- Construct the moment-curvature relationship of all beams including PET strengthened beams utilizing nonlinear stress-strain relationship of PET; and
- Investigate the variable(s) that affects the moment capacity other than fiber type and fiber amount, if any.

For the section analyses, the ACI committee 440 procedure was employed (ACI 440.2R 2008) while the nonlinear σ-ε Model 3 (a polynomial equation) of Fig. 2 was used for the three PET strengthened beams (B-PET, B-HF-5:95, B-HF-10:90). The comparison between test vs. theoretical moments is shown in Table 4 while the results of the moment-curvature analyses are summarized in Table 5.

- Calculation of M_y and M_u using nonlinear PET σ-ε Model 3 (PET) resulted in reasonably accurate theoretical moments comparable to test values (Table 4).
- Strengthening reduced the ductility (Table 5).
- For PET-strengthened beams, ductility improved over that of comparable beams strengthened using CF or GF.
- For the two beams strengthened using hybridized CF-PET, moment and curvature values can be accurately determined at rupture of CF and at final flexural failure, respectively, so that beam sections strengthened using hybridized fibers can be theoretically designed for improved strength and ductility.

Table 4 Comparison between test and theoretical moments

Beam index	Test		Theory			Theory/test		
	$M_{y\text{-test}}$ (kNm)	$M_{u\text{-test}}$ (kNm)	$M_{y\text{-calc}}$ (kNm)	$M_{u\text{-calc}}$ (kNm)		$M_{y\text{-calc}}$/ $M_{y\text{-test}}$	$M_{u\text{-calc}}$/ $M_{u\text{-test}}$	
B-Control	25.9	27.9	23.7	24.2	--	0.916	0.869	--
B-CF	28.1	34.4	25.8	30.9	--	0.917	0.898	--
B-GF	29.7	38.6	25.9	31.9	--	0.871	0.828	--
B-PET	27.1	33.9	25.3	30.0	--	0.932	0.884	--
B-HF-5:95	29.4	36.0	25.6	31.0	28.6 1)	0.871	0.860	0.794
B-HF-10:90	27.2	35.7	25.5	30.0	27.1 1)	0.937	0.850	0.759

Note: 1) Theoretical resisting moment of the beam strengthened using hybridized CF-PET after rupture of CF; 2) all theoretical moment calculations include effect of adhesive.

Table 5 Moment-curvature (M-ϕ) analysis results

Beam index	Yield		Ultimate				Ductility ratio ϕ_u / ϕ_y	
	N/A (mm)	ϕ_y,10^{-5} (/mm)	N/A (mm)	ϕ_u,10^{-5} (/mm)	N/A (mm)	ϕ_u,10^{-5} (/mm)		
B-Control	65.6	2.58	45.8	6.55	--	--	2.54	--
B-CF	68.4	2.66	54.4	5.52	--	--	2.08	--
B-GF	68.6	2.66	55.8	5.37	--	--	2.02	--
B-PET	67.7	2.64	53.1	5.65	--	--	2.14	--
B-HF-5:95	68.2	2.65	54.4	5.51	51.2	5.87	2.08	2.22
B-HF-10:90	68.0	2.65	53.6	5.60	49.3	6.08	2.11	2.29

Table 6 Comparison of theoretical moments w/ and w/o adhesive

Beam index	Yield			Ultimate		
	Adhesive		Difference	Adhesive		Difference
	Yes	No		Yes	No	
B-CF	25.8	25.7	0.39%	30.9	30.8	0.32%
B-GF	25.9	25.7	0.77%	31.9	31.4	1.57%
B-PET	25.3	24.9	1.58%	30.0	27.4	8.67%

It must be stressed that the inclusion of adhesive mechanical properties in the M_u calculation of the beams strengthened using PET is important as shown in Table 6, especially at ultimate stage, because of very low elastic modulus of PET: In Table 1, the secant modulus of PET is only 7.1 GPa while the elastic modulus of adhesive is 1.59 GPa. On the other hand, the consideration of adhesive mechanical properties in the M_u calculation of the beams strengthened using CF or GF is not necessary as shown in Table 6 as the elastic modulus of CF or GF is much high than that of the adhesive.

4. CONCLUSIONS

It is noted that the contents of this technical paper represents a part of on-going research in an attempt to apply PET to flexural strengthening of RC beams and slabs. The following conclusions can be drawn from this study:

(1) PET, despite very low elastic modulus, can be used to strengthen flexural members;
(2) PET, when used with amount equal to about 50% of CF or GF in terms of axial stiffness (E_fA_f), was effective in improving the flexural strength of RC beams;
(3) Failure modes of all RC beams strengthened using PET was ductile flexural failure without any sign of fiber fracture; and
(4) It is recommended that, due to low elastic modulus of PET, the mechanical properties of adhesive must be included in the theoretical moment calculations.
(5) Hybridization of PET with stiffer CF may be an efficient way to overcome low elastic modulus of PET in the future.

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