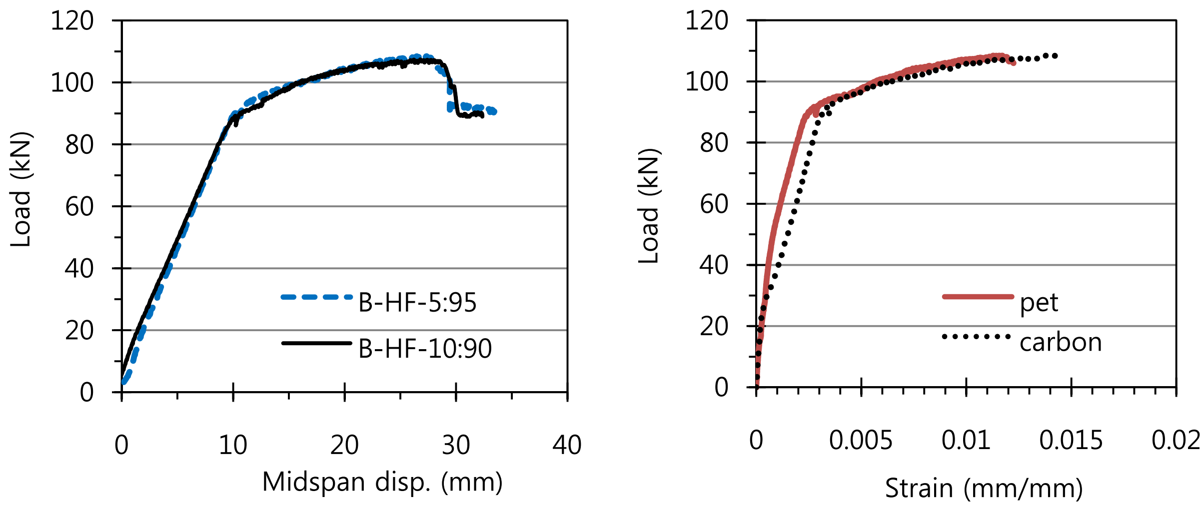

(a) Load vs. midspan displacement (b) Load vs. fiber strain : B-HF-5:95

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)	$\phi_y, 10^{-5}$ (/mm)	N/A (mm)	$\phi_u, 10^{-5}$ (/mm)	N/A (mm)	$\phi_u, 10^{-5}$ (/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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