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EXPERIMENTAL STUDY ON SHEAR BEHAVIOR OF PP-ECC BEAMS WITH DIFFERENT STIRRUP RATIOS

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ABSTRACT

PP-ECC, Polypropylene Fiber Reinforced Engineered Cementitious Composites, as one kind of the fiber reinforced cementitious composites, shows multiple fine cracking, strain-hardening behavior and high ductility under uniaxial tensile tests. The feasibility of application of ECC on structural members with reduction or total elimination of shear reinforcements has been demonstrated by some researchers. However, no further research regarding effects of stirrups on shear carrying capacity of ECC beams have not been studied. In this research, the effects of reducing stirrup ratio in PP-ECC beams were investigated. A normal RC control beam was prepared with providing an amount of stirrups. Furthermore, five specimens using PP-ECC were fabricated with monotonic reducing stirrup ratios from the level of RC control beam to zero. And there is also another RC beam without stirrups in shear span was prepared for comparison. Based on the experimental results obtained, it was found that the shear capacity of PP-ECC beams with increasing stirrup ratios did not increase significantly as that of RC beams. This is because that the shear carried by PP-ECC was decreasing with increase in stirrup ratios. In addition, the increase in stirrup ratio results in significant sliding along the critical crack surface, which damages to the fiber bridging effect and thereby decreases the shear carried by fibers at the peak load.

Keywords: Shear behavior, PP-ECC, stirrup ratio, shear failure.

1. INTRODUCTION

Polypropylene Fiber Reinforced Engineered Cementitious Composites (PP-ECC, referred herein after), as one kind of ECCs, exhibits multiple fine cracking, pseudo strain hardening behavior and

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high ductility under uniaxial tensile loading. Its pseudo strain-hardening behavior results from its unique multiple fine cracking mechanism, in which closely spaced fine cracks forms because of the bridging action of fibers (Li et al. 1998; Maalej and Li 1994). Different from the normal concrete in mixture, ECC generally uses fine aggregates and relatively low volume fractions of short and random fibers (approximately 2 to 3%). Compared to the other ECCs, because the polypropylene (PP) fiber is softer, lower cost, easier dispersing, hydrophobic and has non-polar nature, PP-ECC shows better workability and durability in alkaline environment (Brown et al. 2002). In this research, a cementitious composite combined with fabricated polypropylene fibers with improved bond properties (Figure 1) that exhibits the pseudo strain hardening and multiple fine cracking of ECCs (Hirata et al. 2009) was used. The properties of PP fiber are shown in Table 1.

Although the steel reinforced ECC (R/ECC) structural members such as column and beam-column joints with reduction of shear reinforcements (Li and Fischer 2002; Parra-Montesinos et al. 2005) has been confirmed in literatures, there is little study regarding the effects of stirrup ratios on shear capacity of ECC beams under general loading conditions. In addition, there is no study on the reduction factor of tensile strength of ECC due to the sliding on the crack surfaces. In this research, totaling five PP-ECC and two normal RC beams with various stirrup ratios were tested to clarify shear behavior. The tensile properties of ECC were obtained from uniaxial tensile tests. Furthermore, the reduction factor was evaluated in this study.

2. UNIAXIAL TENSILE TESTS OF PP-ECC

Tensile behavior was investigated by uniaxial tensile tests. PP-ECC material used in this research is a class of short-fiber, randomly distributed cementitious composites with 3% fiber volume fraction and its mix proportion of PP-ECC used in this study is shown in Table 2. The fibrillated PP fiber with rugged surface as shown in Figure 1 results in improvement of bond properties and exhibits the pseudo strain hardening and multiple fine cracking of ECC under tensile stress.

2.1. Specimen layout and test method

Tensile properties of PP-ECC were inspected by employing uniaxial tensile method as shown in Figure 2(a). The setup of specimens for uniaxial tensile tests is shown in Figure 2(b). 0.1 mm/min was selected as the head speed of loading facility.

2.2. Test results

Tensile stress versus strain curves of three specimens are shown in Figure 3. The test result clearly shows typical pseudo strain hardening behavior of ECCs. At the strain around 3%, a localized crack gradually formed and the stress began to decrease slowly. The yield and tensile strength were greater than 2 and 3 MPa, respectively.

3. BEAM TESTS PROGRAM

3.1. Materials

As described in Chapter 2, the mix proportion of PP-ECC used in this study is shown in Table 2. Table 3 gives the mixture proportion of normal concrete with a design compressive strength of 27 MPa. As for steel reinforcements, a regular deformed steel reinforcing bar with nominal diameter of 25.4 mm and yield strength of 400 MPa was used for longitudinal reinforcement in all beam specimens. The stirrups were deformed bar with nominal diameter of 6.35 mm and yield strength of 323 MPa. The round steel bar with diameter of 6 mm and yield strength of 277 MPa was used for steel bar in compression.

3.2. Layout of test specimens

Two different types of matrixes (concrete and PP-ECC), totaling seven beams, including one control beam (RC-Ref), one RC beam without stirrups within the shear span (RC-00) and five PP-ECC beams with varying stirrup ratios from the level of control beam to zero, as summarized in

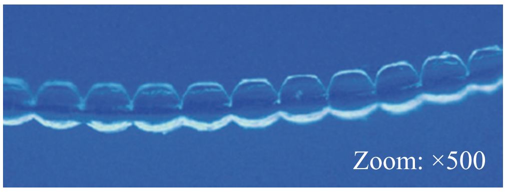
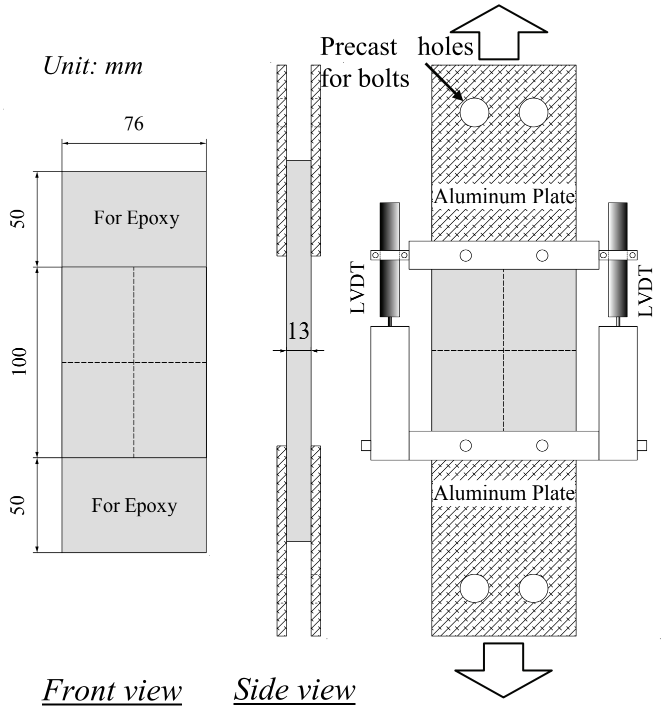


Figure 1: Cross section of PP fiber

Table 1: Properties of polypropylene fiber

Fiber type	Length (mm)	Diameter (μm)	Young's modulus (MPa)	Tensile strength (MPa)
Polypropylene (PP)	12	36	5000	482



(a) Dimensions of specimen (b) Setup of tests

Figure 2: Uniaxial tensile tests of PP-ECC

Table 2: Mix proportion of ECC

W/C	Unit (kg/m^3)			
(%)	Water	Cement	PP Fiber	AE
27	371	1400	27	7

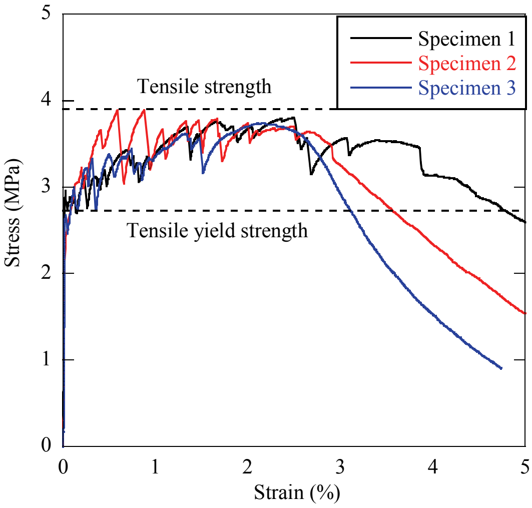


Figure 3: Results of uniaxial tensile tests

Table 3: Mix proportion of concrete

G_{max} (mm)	W/C (%)	Unit (kg/m^3)				
		Water	Cement	Fine aggregate	Coarse aggregate	Superplasticizer
20	60	176.6	294.3	829.9	970.3	2.943

Table 4: Summary of beam specimens

Beam	Length L (mm)	Stirrup		Longitudinal bar		Matrix type
		r_w (%)	s (mm)	A_s (mm^2)	p_w (%)	
RC-Ref	2100	0.42	100	1013.4	2.7	Concrete
RC-00		0.00	–			
RE-42		0.42	100			ECC
RE-30		0.30	140			
RE-24		0.24	175			
RE-12		0.12	350			
RE-00		0.00	–			

r_w is stirrup ratio. s is the spacing of stirrups. A_s is the total area of the cross section of longitudinal reinforcements. p_w is the longitudinal reinforcement ratio.

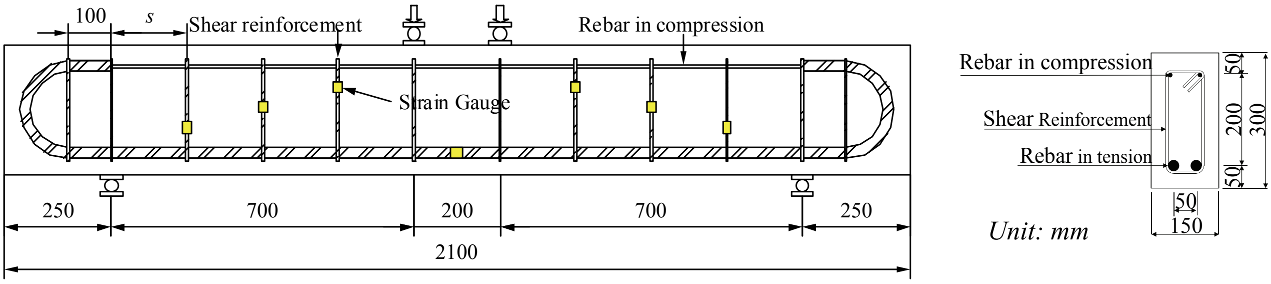


Figure 4: Dimensions and reinforcement details of beams

Table 4, were tested by four-point loading method. The shear span-effective depth ratios *a/d* of all beams were 2.8. The designations of these seven specimens were selected according to their matrix type and stirrup ratio. Except the case of control beam (RC-Ref), the latter digit in specimen designations indicates the stirrup ratio. The dimensions and reinforcements for all beams are shown in Figure 4. All specimens were applied with a monotonic load up to the failure.

4. THE RESULTS OF BEAM TESTS AND DISCUSSIONS

4.1. Load-deflection behaviors and failure mode

The experimental load versus mid-span deflection curves for all specimens involved in this study are shown in Figure 5. The results of all specimens including material tests are summarized in Table 5. The failure modes for all beams were shear tension failure.

4.2. Cracking pattern at the peak load

Figure 6 presents visible cracks of all specimens at the peak load as well as the critical crack developed after the peak load in the interest zone as shown in bold lines with red color. The interest zone for investigation was the zone between longitudinal rebars in tension and compression with height from 50 to 250 mm.

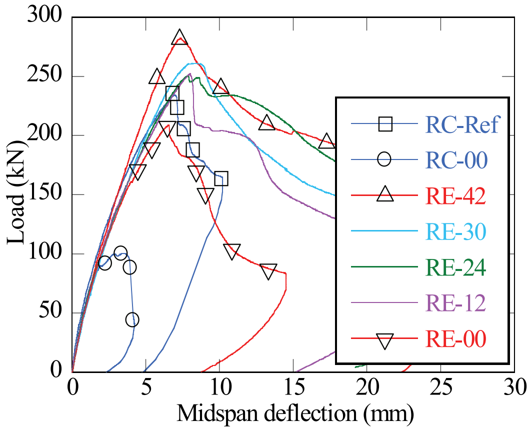


Figure 5: Load vs. mid-span deflection

Table 5: Summary of beam tests

Beam	V_{exp} (kN)	Mid-span deflection (mm)	Compressive strength (MPa)	Tensile strength (MPa)	Tensile yield strength (MPa)
RC-Ref	117.03	6.98	29.1	2.53*	–
RC-00	50.27	3.54	34.9	2.88*	–
RE-42	141.09	7.39	30.4	3.67	2.51
RE-30	130.56	8.44	33.1	3.56	2.30
RE-24	125.24	7.89	31.5	3.39	2.38
RE-12	126.05	8.01	35.6	3.68	2.45
RE-00	104.38	6.55	32.8	3.71	2.50

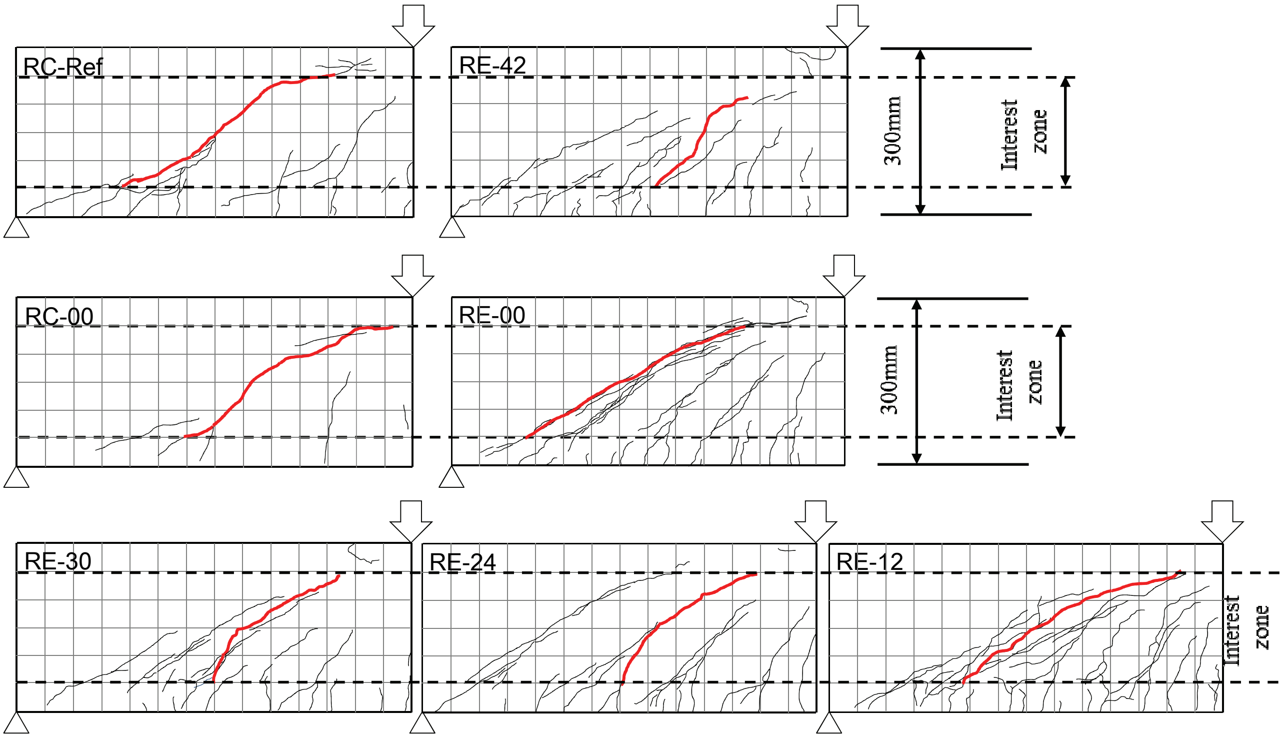


Figure 6: Cracking behavior at the peak load

4.3. Behavior of the critical crack

Kabele et al. (2007) revealed that only a fraction of ECC's tensile strength and strain capacity might be utilized in shear elements due to possible damage of bridging fibers on sliding crack surfaces. To investigate the damage induced by sliding of the critical crack surfaces in the post peak stage, the grid with unit square size of 50 mm×50 mm was marked on the side surface of beams before testing. The points at where the critical crack crossed horizontal lines of the grid were selected to be sample points. As illustrated in Figure 7, by measuring the resultant displacement (ΔL) of sample points, then the opening (δ_{op}) and sliding (δ_{sl}) of the critical crack can be derived from the equations (1) and (2), respectively.

$$\delta_{op} = \Delta L \cdot \sin\theta \qquad (1)$$

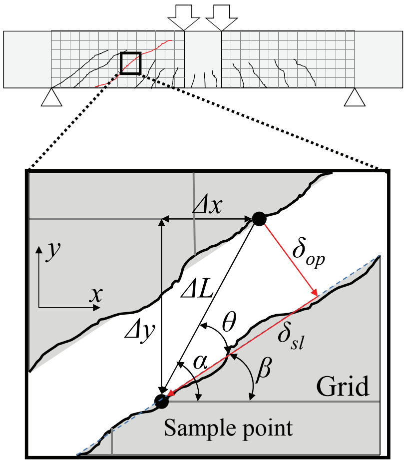
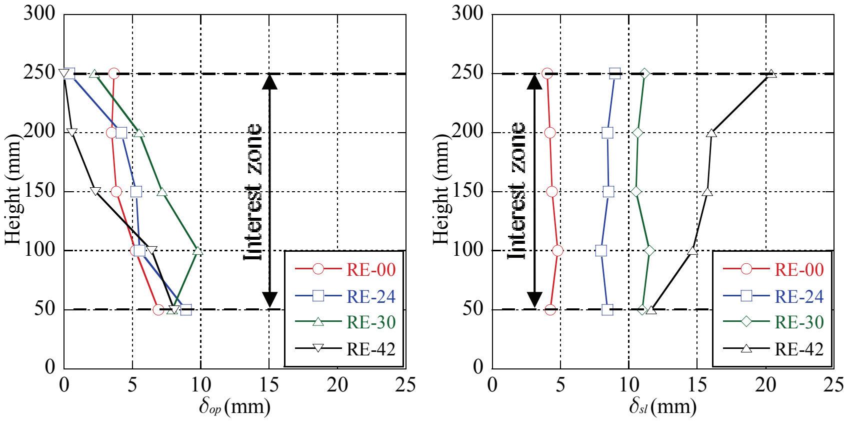


Figure 7: Displacement of a sample point



(a) Opening (b) Sliding

Figure 8: Opening and sliding of the critical crack at 130 kN in post peak stage

$$\delta_{sl} = \Delta L \cdot \cos\theta \tag{2}$$

where, θ is the angle of resultant displacement to the crack surface. The calculated opening and sliding of the critical cracks along the height of beam in the interest zone for four PP-ECC beams (RE-42, RE-30, RE-24 and RE-00) at the load level of 130 kN in the post peak stage were presented in Figure 8. Figure 8(a) shows that the opening of the critical crack along the beam height in the interest zone. Figure 8(b) shows the sliding of the critical crack along the beam height. It exhibits that higher stirrup ratio results in more sliding, which further reveals that the damage to fiber bridging induced by sliding on the critical crack surfaces in PP-ECC beam with higher stirrup ratio at the peak load is more significant.

4.4. Shear resisting proportion

Figure 9 reveals the relationship between shear strength and quantity of stirrups in this study, which implies that the shear reinforcing effect of stirrups in PP-ECC beam is not significant as that in RC beams. In JSCE code, the shear carried by member without shear reinforcements excluding the fiber effects in R/ECC beams (V_c) was defined as equation (3). The experimental shear carried by stirrups (V_{s_exp}) can be obtained from the strain of stirrups which the critical diagonal crack crossed. The strain of stirrups was captured by prepared strain gauges attaching on the stirrups during the tests. Thus, the shear carried by stirrups (V_{s_exp}) can be formulated by equation (4).

$$V_c = 0.7 \times 0.20 \cdot \sqrt[3]{f'_{ECC}} \cdot \sqrt[4]{1000/d} \cdot \sqrt[3]{100 p_w} \cdot b_w \cdot d \tag{3}$$

$$V_{s\_exp} = \begin{cases} \sum_{i=1}^{n} A_w E_s \varepsilon_{si} & \left(\varepsilon_{si} < \varepsilon_y\right) \\ \sum_{i=1}^{n} A_w f_{wy} & \left(\varepsilon_{si} \geq \varepsilon_y\right) \end{cases} \tag{4}$$

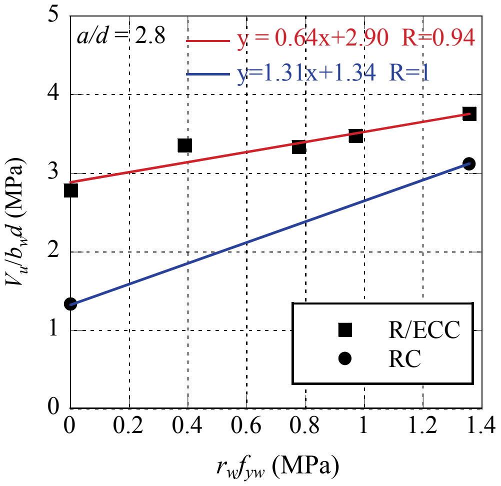


Figure 9: Shear strength versus stirrups

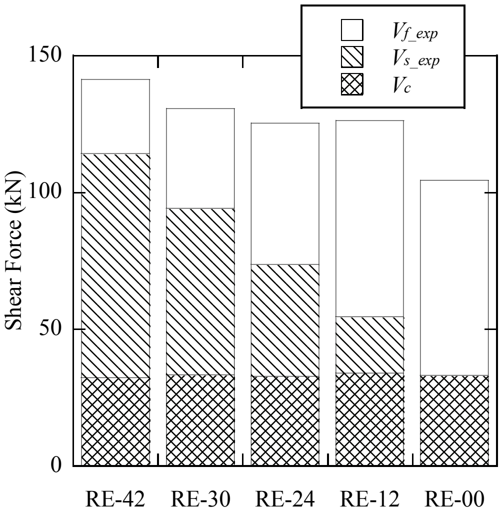


Figure 10: Shear resisting proportion

where, V_c is the shear carried by members without stirrups excluding the fiber effects, f'_{ECC} is compressive strength of ECC (MPa), d is effective depth (mm) and b_w is the web thickness (mm). n is the number of stirrups crossed by the critical crack at the peak load, E_s is the elastic modulus of stirrup, ε_s is the stirrup strain recorded in the tests, ε_y and f_{wy} is the yielding strain and strength of stirrups, respectively. The total shear carried by R/ECC beams (V) and the shear carried by PP-ECC (V_{ECC_exp}) can be formulated by equations (5) and (6), respectively.

$$V = V_c + V_{f\_exp} + V_{s\_exp} \tag{5}$$

$$V_{ECC\_exp} = V_c + V_{f\_exp} \tag{6}$$

$$V_{f\_exp} = V - V_c - V_{s\_exp} \tag{7}$$

where V_{f_exp} is the shear carried by fibers. Based on the equations (3) to (6), V_{f_exp} can be calculated by equation (7). The shear resisting proportion with three components as varying stirrup ratios is shown in Figure 11, indicating that the shear carried by PP-ECC decreased as the increase in stirrup ratio, which resulted from the decrease in the shear carried by PP fibers due to more significant sliding which damaged the fiber bridging effect along the critical crack in PP-ECC beams.

5. CONCLUSIONS

1) Attributing to the fiber bridging effect in PP-ECC, the shear carrying capacity of the beam with stirrups and without stirrups increased 20.6% and 107.6%, respectively by replacing concrete with PP-ECC. The shear carrying capacity can be increased by replacing cement matrix from concrete to PP-ECC, especially in case of lower stirrup ratio.
2) The damage to fiber bridging effect induced by sliding on the critical crack surfaces in PP-ECC beam with higher stirrup ratio at the peak load is more significant compared to the case with lower stirrup ratio, which results in shear carried by ECC in PP-ECC beams decreases as the increase in stirrup ratio.

3) Different from the case of shear resisting proportion in RC beams, in which the shear carried by concrete is almost constant even with varying stirrup ratios and the shear carried by stirrup is proportional to stirrup ratio, the shear carried by ECC in PP-ECC beams decreases as the increase in stirrup ratio. This decrease in shear carried by fibers results from the damage to fiber bridging which is induced by sliding along the critical crack surfaces.

6. ACKNOWLEDGMENTS

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