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Deformation capacity of RC piers wrapped by new fiber-reinforced polymer with large fracture strain

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Abstract

One of the major drawbacks of structure strengthening by fiber reinforced polymer wrapping using materials such as CFRP and AFRP, whose strength and stiffness are high, is the brittle nature of failure mode, which is caused by fracture of the fiber due to low fracturing strain. A series of experiments were conducted to investigate the efficiency of using two new types of fibers, polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) fiber, for seismic strengthening of RC piers. These fibers have the properties of low stiffness and high fracturing strain. Specimens strengthened by PET and PEN fiber sheets wrapping showed considerable improvement in shear capacity and ductility compared to the control specimen. Both PET and PEN showed no tendency to fiber breakage before the predefined ultimate deformation. Pier behaviors such as shear deformation and strain development in both fiber and steel shear reinforcement, and the piers, ultimate failure modes, were carefully examined. Shear deformation increases rather rapidly after peak load and concrete shear capacity decreases with the increase in shear deformation. Stiffness of fiber affects the development of shear deformation and the descending branch of the load–deformation curve after the peak load. A simple model to predict the piers deformation capacity, based on the experimental results, was proposed.

Keywords: Shear; Ductility; Wrapping; PET; PEN; High fracturing strain

1. Introduction

The recent large earthquakes in Japan exposed the vulnerabilities of its existing reinforced concrete structures. The Great Hanshin earthquake revealed that structures designed by the old design code need strengthening of their shear capacity. Furthermore, in the structures with comparatively high shear capacity, it was also noted that increased ductility in order to withstand large seismic action is necessary.

Strengthening of reinforced concrete piers with fiber material jacketing has proven to be able to meet these two demands efficiently. The usage of fiber material in the strengthening scheme is preferable to steel in many cases [1–4] due to the advantages of fiber compared to steel [5,6]. The high strength-to-weight ratio of fiber, resistance to corrosion and easy handling and installation make fiber reinforced polymer (FRP) jackets the preferred material for strengthening.

Due to the above-mentioned advantages, conventional FRP materials such as aramid, carbon, and glass are frequently used for seismic strengthening of reinforced concrete piers. Many researchers have proven the effectiveness of their application in shear and ductility enhancement. However, it should be noted that due to their low fracturing strain capacity, these fiber materials tend to fail sooner due to fiber breakage before the structures can fully utilize their reinforced strength [3,7]. The breakage of fiber causes a loss of confinement and a sudden loss of load-carrying

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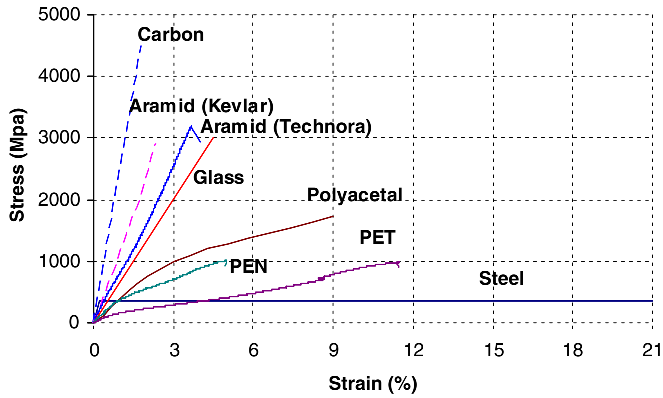

Fig. 1. Stress and strain relationships of various materials.

capacity and directly limits the ductility potential. Because this can lead to sudden failure of the structure, breakage of fiber is not favourable. In the design procedure the limitation of fiber strain is used to determine the reinforced concrete (RC) piers strength capacity to avoid rupture of fiber material [8].

New fiber materials such as polyacetal fiber (PAF), polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) have properties of large fracturing strain and low stiffness in comparison to aramid, carbon, and glass fibers [9–11]. Fig. 1 shows the stress–strain relationships of various fiber materials. Previous studies [9] using polyacetal fiber showed that large fracturing strain fiber is less likely to fracture before the RC piers reach their ultimate deformation. Continuous shear force and enhanced ductility could be gained from the fiber to compensate for the reduction concrete shear capacity due to damage induced by large cracks and seismic action.

The objective of this research is to investigate the shear strengthening and ductility enhancement of reinforced concrete piers confined with high fracturing strain fiber materials, PET and PEN. Based on these test results, models for predicting the ultimate deformation of strengthened RC piers are proposed.

2. Experimental program

2.1. Details of test setup

A total of 15 RC piers in four experimental batches were constructed to represent a rectangular pier of a regular bridge, while the bottom part represented the footing of the pier. The first and second batch specimens were rectangular piers with a cross section of 400 × 400 mm. The third and fourth batches were rectangular piers with dimensions of 600 × 600 mm. The pier cross section areas of third and fourth batches were enlarged to give closer resemblance and response to actual pier dimensions. The size effect was not considered as a parameter in this research. All pier corners were rounded with a rounding radius of 25 mm.

Table 1
Specimens details

Specimen	f'_c	a/d	ρ_t (%)	ρ_w (%)	ρ_f (%)	Fiber material
First batch						
SP1	29.5	3	2.87	0.16	–	–
SP2	29.5	3	2.87	0.16	0.13	A2
SP3	29.5	3	2.87	0.16	0.38	PEN
SP4	29.5	3	2.87	0.16	0.37	PET
Second batch						
SP5	31.7	3	2.87	0.16	0.19	PET
SP6	31.7	4	2.87	0.16	0.12	PET
SP7	31.7	4	2.87	0.16	0.06	PET
SP8	31.7	4	2.87	0.16	–	
SP9	31.7	4	3.59	0.16	0.12	PET
SP10	31.7	4	2.15	0.16	0.06	PET
Third batch						
SP11	31.7	4	2.82	0.2	0.25	PET
SP12	31.7	4	2.82	0.2	0.125	PET
Fourth batch						
SP13	34.5	3	2.82	0.2	0.29	PET
SP14	23.7	3	2.82	0.09	0.42	PET
SP15	31.1	3	2.82	0.09	0.42	PEN

Table 2
Shear capacities

Specimen	V_c (kN)	V_s (kN)	V_{tot} (kN)	M_u (kN m)	V_u (kN)	V_{tot}/V_u	Ductility
First batch							
SP1	151	79	230	331	288	0.8	5.09
SP2	151	79	230	331	288	0.8	11.84
SP3	151	79	230	331	288	0.8	10.65
SP4	151	79	230	331	288	0.8	11.42
Second batch							
SP5	155	79	234	334	290	0.8	7.98
SP6	155	79	234	334	223	1.05	9.05
SP7	155	79	234	334	223	1.05	8.46
SP8	155	79	234	334	223	1.05	7.40
SP9	169	79	248	401	267	0.93	8.76
SP10	151	79	230	265	177	1.3	10.41
Third batch							
SP11	318	206	524	1018	463	1.13	8.52
SP12	318	206	524	1018	463	1.13	7.54
Fourth batch							
SP13	327	105	432	1051	637	0.84	7.76
SP14	289	83	372	1010	612	0.61	4.12
SP15	316	83	399	1058	641	0.62	6.87

Tables 1 and 2 give details of the test specimens. The first and second batch specimens used 19 mm deformed bars for longitudinal reinforcement and 6 mm deformed bars for stirrups. The third batch specimens used 25 mm deformed bars for longitudinal reinforcement and 10 mm deformed bars for stirrups. The fourth batch specimens used 25 mm deformed bars with differing shear reinforcement ratios. SP13 of the fourth batch used 10 mm deformed bars for stirrups, while SP14 and SP15 of the fourth batch used 6 mm deformed bars for stirrups. The longitudinal reinforcements in the piers were extended into