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Shear strengthening of corroded reinforced concrete columns using pet fiber based composties

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ABSTRACT

Polyethylene terephthalate (PET) fiber-reinforced polymer (FRP) composites are characterized by a large rupture strain (LRS) (usually larger than 5%) but a low elastic modulus compared to conventional FRP materials made of carbon, glass, and aramid fibers. Previous studies have proved that the use of PET FRP sheets as jacketing materials for plain concrete or reinforced concrete (RC) columns could efficiently enhance their ductility. This paper presents a combined experimental and analytical study on the shear strengthening of corroded RC columns with stirrups having different levels of corrosion before strengthening. The shear resistance contributions from the substrate column and PET FRP sheets at various volume ratios were carefully examined and their interaction mechanisms were discussed. Design equations following a conventional truss analogy were then proposed to predict the shear strength of PET FRP-wrapped columns considering the effect of stirrup corrosion, and the predictions were verified against the test results.

1. Introduction

Recently, many design specifications have required the confinement of hinge regions at the ends of reinforced concrete (RC) columns and beams to ensure their seismic resistance [1,8,20], (GB 50010-2010, etc.). However, field observations indicated that this requirement was usually not satisfied in many RC buildings. Many structures were reported to fail owing to inadequate confinement in RC columns. This was caused by largely spaced or insufficient hoop reinforcements, as reported after the 2008 Sichuan earthquake in China [40], 2010 Maule earthquake in Chile [43], 2011 Vann earthquake in Turkey [7], and 2014 Yunnan earthquake in China [10]. A large hoop spacing and lack of stirrup anchorage at the plastic hinge locations of columns also lead to spalling of the covering concrete and buckling of column longitudinal bars in concrete columns under the effect of earthquake-induced reversed moments.

Apart from the lack of lateral reinforcement, reinforcement corrosion has been observed, particularly in marine environments. Corrosion damage is usually observed as rust stains and minute cracking over the concrete surface running parallel to the underlying steel bars because of the volume increase associated with the formation of corrosion products. Reinforcement corrosion reduces the beam and column capacity owing to steel area losses, bond deterioration, and reduction in the effective concrete area [17,18,24,35,37]. Although many studies on the effect of reinforcing steel corrosion on the flexural capacity of RC columns have been carried out (Ma et al., 2012), [42], there are few studies on the reduction in shear capacity of RC columns due to the corrosion of stirrups [41]. Actually, because stirrups are nearer to the concrete surface than the longitudinal steel bars, they are the first to be attacked by chlorides in a chloride environment.

Extensive investigations on the seismic retrofitting of RC columns have proven the effectiveness of conventional fiber-reinforced polymer (FRP) materials such as aramid, carbon, and glass FRP in shear and ductility enhancement [6,4,5,39]. Several shear design models have been proposed in design specifications [2,9,14,16,22], considering the benefit of the shear resistance of FRPs and their confinement to the core concrete. However, conventional FRPs tend to fail sooner owing to the brittle breakage of fibers, which causes the loss of confinement, load-carrying capacity, and ductility potential.

New fiber materials such as polyacetal, polyethylene naphthalate (PEN), and polyethylene terephthalate (PET) have a larger fracture strain and lower elastic modulus compared to conventional fibers [38,21,4]. Previous studies [3,11,13,33] proved that concrete or RC members wrapped with PET and PEN FRP sheets could

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efficiently enhance their ductility regardless of their low elastic modulus. Other high deformable composites with large rupture strain (LRS) such as polypropylene fiber ropes [28,31], vinylon or aramid fiber ropes [29,30], ultra-high molecular weight polyethylene (UHMEPE) types [30], Velcro tapes [23] and hybrid composites [28] were proved their efficiency in improving the ductility of RC columns as well. The large rupturing strain allows the fiber to contribute sufficient shear force at the ultimate state while avoiding fiber rupture, which is beneficial to have ductile shear failure [21]. Despite the fact that there have been many studies investigating the effect of steel corrosion on RC members wrapped with conventional FRPs [25,36], the effect of the stirrup corrosion on the respective shear component of the substrate RC member and the PET FRP sheet as well as the corresponding mechanisms are still unclear. Moreover, there is lack of design equations to predict the shear strength of corroded RC columns wrapped with PET FRP sheets, which is an obstacle to the design, assessment, and life prediction of such members.

In a previous conference paper published by the authors, the effect of stirrup corrosion and PET wrapping on the failure mode, cracking load, peak load, and energy dissipation was reported [44]. Following that study, the main objectives of this research are a) to investigate the effect of stirrup corrosion on the shear resistances of the PET FRP sheet and substrate RC column, and b) to develop a rational design model to predict the shear capacity of corroded RC columns wrapped with PET FRP sheet. The shear contribution of each component is determined by the measured strains of the PET FRP sheet and the load–deflection responses. The proposed models consider the shear resistance of the substrate RC and PET FRP sheet, and the effect of steel corrosion is reflected in each component. The results of the proposed models are verified against test results.

2. Experimental program

The detailed experimental program is available in Zhang et al. [44]; therefore, only a brief introduction is presented here.

2.1. Details of test setup

Twelve RC rectangular columns consisting of four unstrengthened control specimens with different levels of stirrup corrosion (0, 10%, 15%, and 25%, as indicated by the number following "C-" in Table 1) and eight strengthened specimens with different layers of PET FRP sheet wrapping (1or 2 layers, as indicated by the number following "L-" in Table 1) were tested.

The cross section of the substrate column was 250 × 250 mm with a total height of 740 mm. The footings had a size of 700 × 450 × 360 mm (length × width × height). Each specimen had eight 25 mm ribbed bars for longitudinal reinforcement and 10 mm plain bars for stirrups spaced at 100 mm. Details of the reinforcement arrangement are shown in Fig. 1. The average 28 d compressive strength of three concrete cubic (150 × 150 × 150 mm) was 32.7 MPa. Tables 2 and 3 provide the properties of the steel reinforcement and PET FRP sheet used in this experiment, obtained through uniaxial tensile tests of three respective specimens. The specimens were designed to be shear-insufficient to focus on their shear behaviors. Prior to the strengthening, an accelerated corrosion procedure suggested by Zhang et al. [45] was applied for stirrup corrosion and the longitudinal reinforcement was inhibited from corrosion with epoxy resin coating at its intersection with stirrup. Details of this procedure can be found in Zhang et al. [45,44].

Table 1
Parameters of tested specimens.

Specimen	Expected degree of corrosion η_e (%)	Number of PET layers	Volume ratio of PET ρ_f (%)
C-0-L-0	0	0	0
C-0-L-1	0	1	0.67
C-0-L-2	0	2	1.35
C-10-L-0	10	0	0
C-10-L-1	10	1	0.67
C-10-L-2	10	2	1.35
C-15-L-0	15	0	0
C-15-L-1	15	1	0.67
C-15-L-2	15	2	1.35
C-25-L-0	25	0	0
C-25-L-1	25	1	0.67
C-25-L-2	25	2	1.35

2.2. Instrumentation and testing procedure

The specimens were subjected to a combination of cyclic horizontal load and constant axial load, as shown in Fig. 2(a) and (b). The compressive vertical load was maintained as 180 kN, which is approximately 30% of the expected axial loading capacity of the non-corroded control column. A 500 kN closed-loop MTS actuator was used to apply the horizontal cyclic load. Load increments and displacement increments between adjacent load cycles are illustrated in Fig. 2(c), in which U_{b1} = 20 kN for load control and U_{b2} is the displacement at the yielding of the tension reinforcement for displacement control. Each controlling step lasted for one cycle.

Four transducers (LVDTs) were used to measure the displacement, as indicated in Fig. 2(a). Strain gauges were used to measure the strain development in the PET FRP sheet. The strains were in the PET fiber direction and distributed in rows and columns at an interval of 70 × 50 mm. The total number of strain gauges on the shear face was 20 for the PET-wrapped specimens. The location of strain gauges attached to the PET fiber is shown in Fig. 3. Load, displacement, and strain outputs were recorded during the tests using a computer connected to a recording system. Unfortunately, no data was obtained from specimen C-0-L-2 owing to some unexpected problems in the recording system; consequently, its results are not included in the following section.

3. Results and discussions

3.1. Failure modes

After accelerated corrosion procedure, horizontal cracks of concrete along stirrups were observed along the corroded stirrups for all levels of corrosions, which can be attributed to the rust expansion of stirrups. The width of concrete cracks increased with the increase of the degree of corrosion. No longitudinal corrosion cracks were observed since the longitudinal reinforcements were prevented from accelerated corrosion.

During loading of specimens, all un-wrapped specimens showed brittle shear-compression failure with extensive X shape diagonal concrete shear cracks. For all PET fiber sheet wrapped specimens, no breakage of the PET FRP sheet occurred till the end of the test, while crushing of concrete was also noticed after removing the PET FRP sheet. For all the specimens, no bucking of longitudinal reinforcements was observed. More details of failure modes can be found in Zhang et al. [44].

3.2. Corrosion damage

After loading the test specimens to failure, the stirrups were extracted, cleaned, and used to calculate the mass loss following the standard ASTM G1-03 (2011). Four coupons with a length of 100 mm within the targeted 300 mm long corrosion area per stirrup per column were used. The weight of the stirrup without corrosion was determined by weighing the 100 mm long stirrup in the