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SEISMIC PERFORMANCE OF RC COLUMNS STRENGTHENED WITH DYNEEMA FIBER-REINFORCED POLYMER SHEETS

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ABSTRACT

Dyneema fiber is a new type of composite material with great performances on ultimate tensile strain and energy absorption superior than other fiber sheets such as aramid and carbon fiber sheets. An experimental investigation was conducted to study the seismic behavior of reinforced concrete columns strengthened with DFRP (Dyneema Fiber Reinforced Polymer) sheets and dry Dyneema fiber sheets (DFS) without resin impregnation. All specimens were tested under cyclic lateral shear force with constant axial load. Test variables included axial load, reinforcing ratio of the FRP sheets, column height-to-diameter ratio and the polyester resin. Test results show that seismic resistance of retrofitted columns can be improved significantly as a result of the confining action of the DFRP sheets. It is confirmed that the seismic performance of RC circular columns can also be improved with dry Dyneema fiber sheets without resin impregnation and bonding due to its good energy absorption.

Keywords: Columns, Dyneema fibers, DFRP, Seismic retrofitting

INTRODUCTION

The use of fiber reinforced polymers (FRP) represents an innovative and effective technology for strengthening, retrofitting and upgrading of existing concrete structures due to their much more beneficial characteristics such as high strength and stiffness to weight ratio, high corrosion resistance, electromagnetic neutrality, inherent tailor ability and ease of the field applications (Saadatmanesh et al. 1996,1997; Xiao et al, 1999; Gould, N.C and Thomas G. Harmon, 2002; Sheikh, S. A. and Grace Yau,2002; Wu et al.,2003,2006). The most popular FRP composites used in structural retrofitting are CFRP, GFRP and AFRP. Various FRP composites often have its special weakness. For example: (1) the ultimate strain and energy absorption of CFRP composites are considered low if it is used to improve the ductility of existing columns; (2) the durability of GFRP used in some severe environments is not satisfied. Dyneema fiber is a new type of composite material. It has many advantages like these existing composites, and more, it has great performance on ultimate tensile strain and energy absorption superior than other fiber sheets such as aramid and carbon fiber sheets.

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This paper is focused on investigating the mechanical properties of DFRP composites, the effectiveness of improving the seismic performance of RC columns strengthened with DFRP composites. Experimental study was also conducted to show that the seismic performance of RC circular columns can also be improved with dry Dyneeema fiber sheets without resin impregnation and bonding due to its good energy absorption.

MECHANICAL PROPERTY OF DFRP SHEETS

Due to lack of data on mechanical properties, a flat coupon tests was conducted following the JSCE recommendation (JSCE 2001). Dimensions of the test specimens are shown in Figure 1. Two strain gauges were set at mid-length on the two sides of the test coupon. The normal thickness provided by the manufacturer is 0.258mm. Total ten flat coupons were tested and the results are shown in Table 1. The failure modes of flat coupons are shown in Figure 2. The average tensile strength of DFRP sheets is about 1832MPa, the average elastic modulus is about 60GPa, and the average ultimate strain is 3.08%.

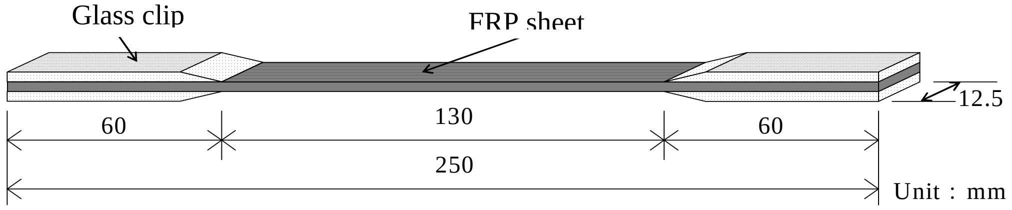


Figure 1 Dimension of flat coupons for tensile tests

Table 1 Results of DFRP sheets tensile tests

No. of Specimens	Actural Width of FRP (mm)	Maximum load (kN)	Ultimate strain (%)	Tensile strength (MPa)	Elastic modulus (MPa)
1	12.80	5.712	3.081	1729.65	56139.28
2	12.97	5.792	3.161	1730.89	54757.60
3	12.80	6.443	3.105	1951.10	62844.21
4	12.86	5.992	3.334	1805.97	54175.35
5	12.50	5.503	2.919	1706.39	58448.25
6	12.84	6.634	3.417	2002.62	58615.68
7	12.46	5.418	2.629	1685.43	64119.76
8	12.75	5.899	2.933	1793.28	61148.20
9	12.85	6.774	3.278	2043.32	62330.89
10	12.54	6.064	2.937	1874.32	63808.68
Ave	12.74	6.02	3.08	1832.30	59638.79

Typical stress-strain curves of different FRP composites such as high modulus CFRP sheet, high strength modulus CFRP sheet, PBO sheets, GFRP sheets, PC strand, steel bar and DFRP sheets are shown in Figure 3. It can be found that the ultimate strength and elastic modulus of DFRP composite are both lower than high strength modulus CFRP sheet, PBO sheets, so it has lower efficiency when used for flexural or shear strengthening of RC beams than that of high strength modulus CFRP sheet and PBO sheets. However, it should be noticed the DFRP composites has the maximum ultimate strain among the existing FRP composites. So it is expected that the use of the DFRP will dominate the confinement of RC columns to improve the seismic performance, especially the ductility.

Figure 2 Failure modes of flat coupons

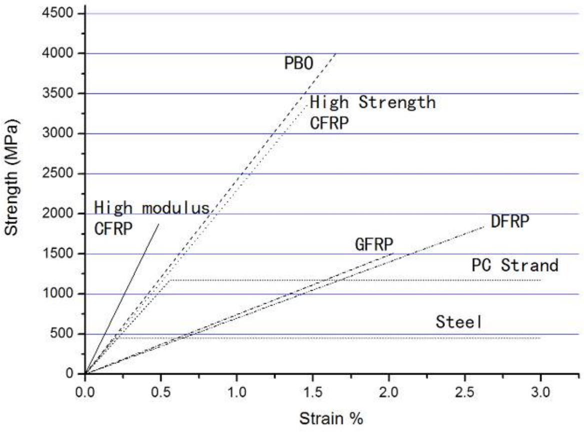


Figure 3 Typical stress-strain curves of some reinforced materials

SEISMIC RETROFITTING OF RC COLUMNS WRAPPED WITH BONDED DFRP SHEETS

Experimental program

Seven large-scale reinforced concrete columns were constructed and tested to investigate the retrofit effectiveness of the DFRP jacketing systems. As shows in Fig.4, the 1000mm(or 1300mm)-tall and 360mm-diameter model columns were reinforced with 12 deformed No.25(nominal diameter=25mm) bars that constituted a longitudinal steel ration of 5.8% of the gross area of column section. All columns were cast integrally with a 1550mm×600mm×700mm stub. Round No.6(diameter=6.5mm) hoops spaced at 150 mm were used as transverse reinforcement. The actual strength of steel bars was shown in table 2, which was obtained from tensile coupon tests. The average strength of concrete was 34.9MPa by the test of cylinders made at the same time with columns.

The region of 100mm from the stub face was strengthened with additional eight D25mm bars, and the he D10mm ties were placed at a spacing of 30 mm within this region to minimize the chances of failure at the section of the stub face. All the specimens were tested under constant axial load and cyclic lateral excursions simulating seismic loading conditions.

Details of the specimens are shown in Table 2. According to aspect ratio, circular columns were classified as two kind, designated as “CH” and “CL” in table2.

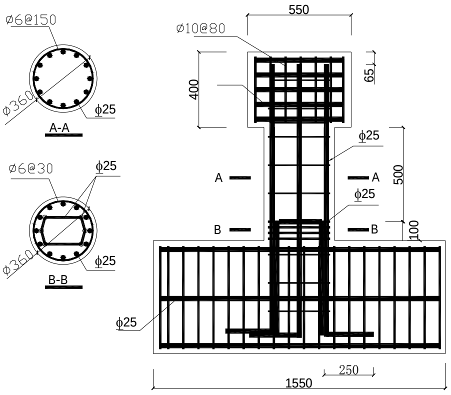


Fig.4 As Built Column Details

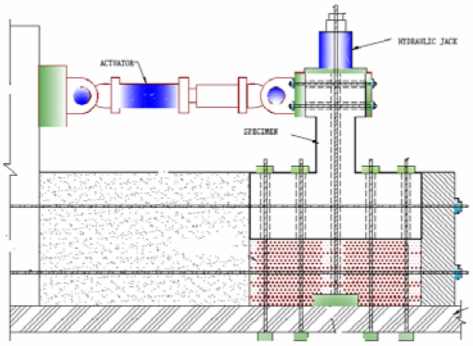


Fig.5 Test setup

Testing

The test setup is shown in Fig. 5. A hydraulic jack with a capacity of 3000kN was used to apply the axial load that was measured by a load cell. The cyclic lateral load was applied by an actuator with a 1000kN load capacity and a 200 mm stroke capacity. The load cycles were divided into two phases: load control and displacement control. Load control phase was used up to yielding of the longitudinal bars, beyond that point, a displacement control load sequence was used. The lateral load sequence consisted of three cycles each to Δ, 2Δ, 3Δ ... and so on, until the specimen was unable to maintain the applied lateral load. Deflection Δ was defined according to the method advised by xiao, 1999. Several strain gages were installed on the longitudinal reinforcement, spiral reinforcement and DFRP sheet to monitor the development of strain.

Table 2 Details of test specimens

Specimen	DFRP treatment	f'_c (MPa)	H/D	Axial load (kN)	Longitudinal rebars				Lateral rebars			
					No.	D_s (mm)	f_y (MPa)	f_{ult} (MPa)	D_s (mm)	S (mm)	f_y (MPa)	f_{ult} (MPa)
CH0	No	34.9	3.1	1200	12	25	382．4	571．1	6	150	319．8	474．4
CH1	1.5 layer	34.9	3.1	1200	12	25	382．4	571．1	6	150	319．8	474．4
CH2	2.5 layer	34.9	3.1	1200	12	25	382．4	571．1	6	150	319．8	474．4
CL0	No	34.9	2.2	1200	12	25	382．4	571．1	6	150	319．8	474．4
CL1	2.5 layer	34.9	2.2	1200	12	25	382．4	571．1	6	150	319．8	474．4
CL2	3.0layers	34.9	2.2	1200	12	25	382．4	571．1	6	150	319．8	474．4
CL3	4.0layers	34.9	2.2	1200	12	25	382．4	571．1	6	150	319．8	474．4

Note: CH designates Circular High columns, CL designates Circular Low columns, H/D=height/diameter

Load-displacement response

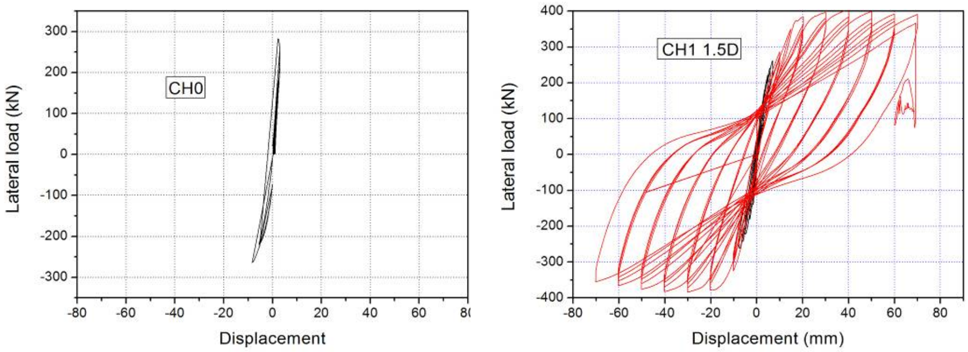
The lateral load-displacement hysteretic relationships for the specimens are shown in Fig.6. It should be noted that these figures have been plotted to the same scale except specimen CH2. Because the columns were symmetrically reinforced with respect to the positive and negative sides for each specimen, the resulting positive and negative portions of each specimen's hysteretic loops should be symmetrical and identical in values. However, due to a limitation of the hydraulic actuator, the maximum strokes reached in the positive and negative directions were slightly different for some of the test specimens.

The hysteretic relationship for the specimen CH0 is shown in Fig.6(a). The maximum lateral load was 280kN. The specimen almost had no ductility because it was controlled by brittle shear failure after the longitudinal reinforcement yield.

The lateral response of specimen CH1 strengthened with 1.5 layers DFRP sheets exhibited a significant improvement with stable hysteretic loops up to the displacement ductility level of u=6, as shown in Fig.6(b). The maximum shear force of CH1 was 390kN, 39.3% higher than the control column. Fig.6(c) shows the hysteretic loops of circular columns CH2 strengthened with 2.5 layers DFRP sheets. The maximum lateral load was 416kN, only a little improvement than the specimen of CH1, while the lateral displacement reached 200mm. The specimen had no sign to fail. For safety, the loading was applied only with push direction until the end. The advantage of DFRP composites for improving the seismic performance of RC columns was obviously confirmed.

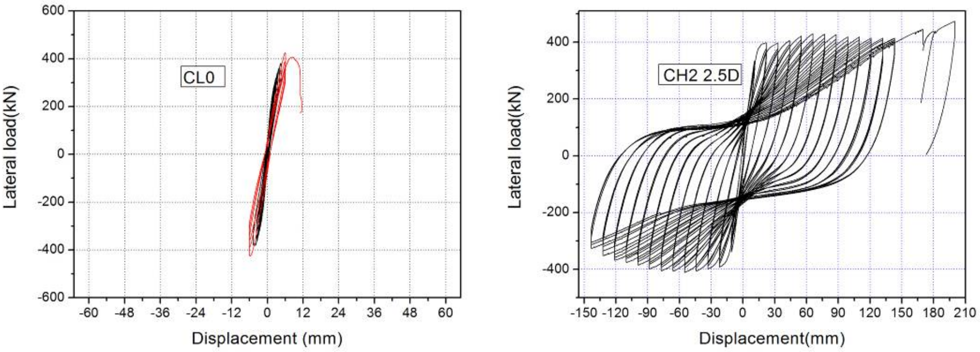
A similar behavior was shown by CL specimens. The maximum lateral load of no retrofit column was 425kN. The specimen was controlled by brittle shear failure after the longitudinal reinforcement yield.

Lateral load-displacement hysteretic relationship for specimens CL2 and CL3 are plotted in Fig.6(e) (f). The maximum lateral load of CL2 was 565kN at u=3 and after this stage specimen showed light degradation in its strength due to concrete deterioration. Fig. 6(f) shows the lateral load-displacement hysteretic relationship for the specimen CL3 confined with 4 layers DFRP sheets. The response of the specimen shows a great improvement of the displacement from 36mm to 54mm due to the higher confinement than specimen CL2. The strength degradation is not obvious.



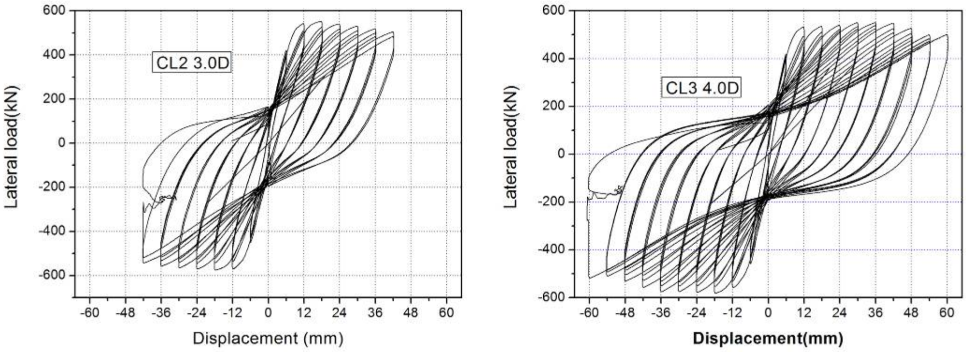
(a) CH0

(b)CH1



(c) CL0

(d)CH2



(e)CL2

(f)CL3

Fig. 6 Lateral load-displacement responses

Failure modes

Typical failure modes of the specimens are shown in Fig.7. The column without retrofitting was controlled by a brittle shear failure after the yielding of longitudinal reinforcement. The specimen CH1, strengthened with 1.5 layers DFRP sheets, failed with the sudden rupture of DFRP sheets. However, the specimen CH2, strengthened with 2.5 layers DFRP sheet, did not rupture until the ultimate stage because of the strong confinement. The flexural crack in the plastic hinge zone was too wide and the longitudinal reinforcement fractured as shown in Fig7(b). Since the short column's height-to-diameter ratio was small, specimen CL3 failed with the rupture of the DFRP despite the confinement with 4 layers DFRP sheets. However, it should be noted the achieved displacement ductility of all the specimens was in excess of 6.0, which is often the minimum value required in high seismic area.

(a) CH1 (b) CH2 (c) CL0 (d) CL3

Fig.7 Typical failure modes

SEISMIC RETROFITTING OF RC COLUMNS WITH DRY DFRP SHEETS

The strengthening effect is of reduced efficiency if the fibers are used for strengthening without resin impregnation due to their inefficient energy absorption. Dyneema fiber sheets are expected to have a good effect to strengthen RC structures even without resin impregnation due to its good energy absorption. It can provide possibility of using dry Dyneema fiber sheets to strengthen RC structures in unfavorable environment such as retrofitting of structures underwater.

Test specimens

Three specimens referred here are part of another series of test conducted to investigate the seismic performance of FRP-confined concrete columns. The column height-to-diameter ratio was 2.8. A constant axial load of 100kN was determined to apply for all columns, based on a nominal axial ratio $P/f_c^{'}A_g = 0.05$. Fig.8 shows the geometric details of column specimens. The diameter of the columns was 300mm. These columns were reinforced longitudinally with 12D19mm bars, resulting in a longitudinal reinforcement ratio of 3.3%. Transverse confinement was provided by D6mm steel wire hoops spaced at 80mm. The average yield stress for the longitudinal and transverse reinforcement were 400MPa and 350MPa respectively.

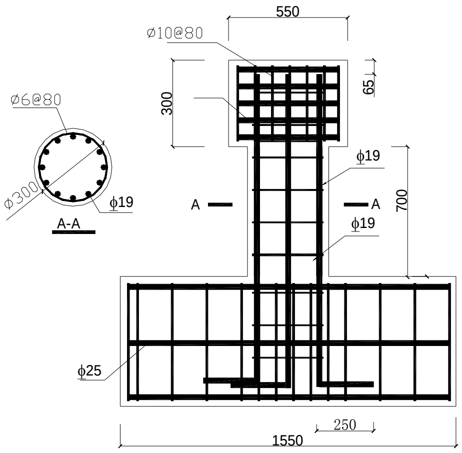


Fig.8 As Built Column Details

One of this three specimens was used as control column (Fig.9(a)). One specimen was completely wrapped with 2 layers of FRP composite straps. As the strap was wrapped around the column, epoxy was applied to the surface and the multiple layers of the strap were adhered together to from a single composite wrap with the desired thickness (Fig.9(b)). The third specimen was confined with 2 layers of Dyneema fiber composite, and no epoxy was used except the 150mm long joint (Fig.9(c)).


(a) C-0 (b) C-Ⅰ (c) C-Ⅱ without epoxy resin

Fig.9 General views of specimens

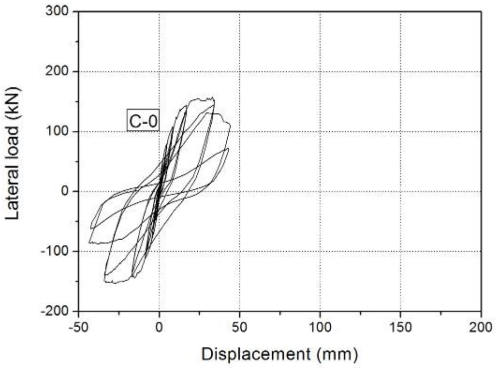
Test setup and instrumentation

The test setup was designed for testing column-footing assemblages subjected to combined axial and lateral loadings. First, the axial load of 100kN was applied to the column by prestressing a pair of 25mm-diameter high-strength steel rods against the base beams of the test frame, which was bolted to the concrete floor. This load was applied to simulate the dead load on the columns. Next, the reversing lateral forces were applied to the column by a hydraulic actuator mounted on the action frame. Each column was instrumented to monitor the applied displacement and corresponding loads, strains and deformations. Four types of instruments including the calibrated load cell, displacement transducer of the actuator and electrical-resistance strain gages were used to measure the various quantities.

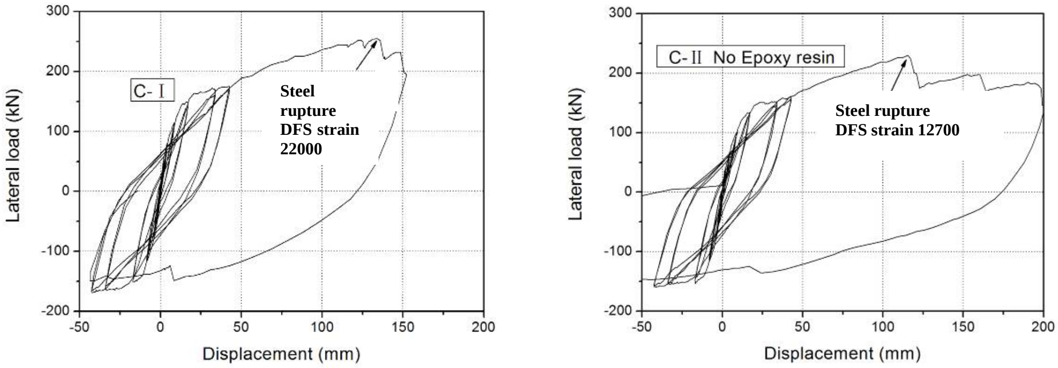
The test was in a displacement control mode following the Japanese standard (reference 1). At initial stage, the lateral load sequence consisted of one cycle to a displacement of L/800，L/400, and two cycles each to L/200、L/100、L/50、L/25、L/20, and after then the specimen was pushed directly until the failure occurred. The letter “L” indicates the length of column. The hysteretic loops of applied lateral loads versus the column free end displacement at the point of application of the load were continuously plotted and updated on the computer during the test.

Load- displacement response

Fig.10(a) shows the hysteretic loops for the no retrofit column C-0. The maximum lateral load of 155kN was recorded. When the load was applied towards the first cycle of L/100, the specimen suffered shear failure after the longitudinal reinforcement yield. The lateral response of specimen C-Ⅰ strengthened using epoxy resin showed a significant improvement with stable hysteretic loops up to the displacement level of 135mm, as shown in Fig.10(b). The maximum shear force of specimen C-Ⅰ was 250kN which was 61.3% higher than the control column. The lateral response of specimen C-Ⅱ strengthened without epoxy resin, also showed a significant improvement with stable hysteretic loops up to the displacement level of 116mm, as can be seen in Fig.10(c). The maximum shear force of specimen C-Ⅱ was 228kN, 47.1% higher than the control column. The maximum load and displacement of specimen C-Ⅱ were about 91.2% and 85.9% of the C-Ⅰ specimen. So the seismic performance of RC circular columns can also be improved with dry Dyneema fiber sheets without resin impregnation and bonding due to its good energy adsorption.



(a) C-0



(b) C- Ⅰ (c) C- Ⅱ

Fig.10 Lateral load-displacement responses

Failure modes

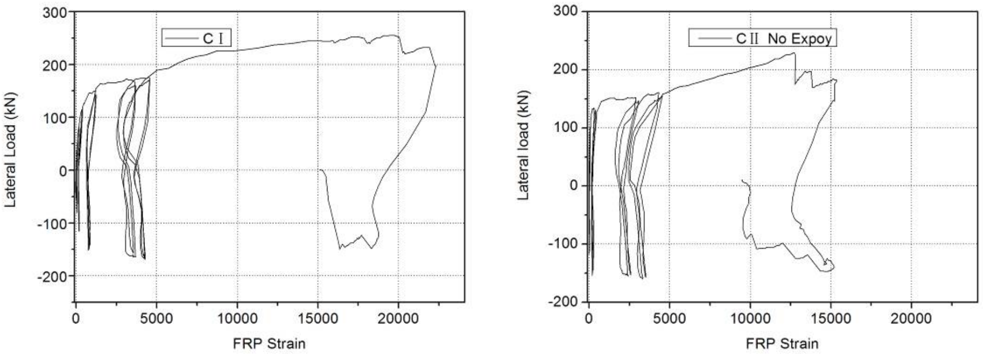
Typical failure modes of the specimens are shown in Fig.11. The specimen C-0 suffered shear failure. The confinement of the specimen C- Ⅰ and C- Ⅱ from 2 layers of FRP was strong enough, and the DFRP sheet did not rupture until the ultimate stage. The flexural cracks in the plastic zone were too wide and the longitudinal reinforcement fractured which are shown in Fig.(11) .

(a) C-0 (b) C- Ⅰ (c) C- Ⅱ

Fig.11 Typical failure modes

Load –strain relationship

Variation of the relationship between lateral load and circumferential strain can be used to evaluate the effects of Dyneema fiber. Fig.12 shows lateral load versus circumferential strain of the same location, about 50mm above the top face of the footing. In this case, ultimate strain of specimen C-Ⅰ was 22000 , about 71% of the ultimate tensile strain by the flat coupon test. The ultimate strain of specimen C-Ⅱ was 15200, about 50% of the ultimate tensile strain by the flat coupon test, and about 68% of that of the specimen C-Ⅰ.



(a) C-Ⅰ (b) C-Ⅱ

Fig.12 Lateral load versus DFRP strain (the location50mm above the footing)

SUMMARY AND CONCLUSIONS

The following conclusions can be drawn from this study:

(1) The feasibility and priority of using DFRP sheets for retrofitting the seismic performance of RC columns are investigated. A great ductility can be achieved through a rational design of retrofitting.

(2) Seismic performance of RC circular columns can also be improved with dry Dyneema fiber sheets without resin impregnation and bonding due to its good energy absorption.

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