SEISMIC RETROFIT OF RC MEMBERS USING FRP WITH VERY LOW YOUNG'S MODULUS

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ABSTRACT :

This paper proposes a use of fiber reinforced polymers (FRP) with very low Young's modulus to solve various issues of ordinary FRP's. "Super Reinforced with Flexibility (SRF)" is a polyester fiber reinforced polymer which has 1/40 of Young's modulus, 1/35 of tensile strength, 10 times larger fracture strain, and 2/3 of price compared to carbon fiber reinforced polymer (CFRP). SRF has potential to substitute CFRP for its high seismic performance and ease of construction. In an experimental program, two identical structural wall specimens with eccentric openings and five cantilever column specimens were constructed with and without SRF strengthening to study effects of SRF on the shear and confining mechanisms. Strengthened specimens showed larger shear strengths and ductility. Test results were studied to consider the resisting mechanism of concrete structures strengthened with SRF.

KEYWORDS: Seismic retrofit, SRF, FRP, Low Young's modulus, RC structural walls with openings, ductility, RC columns

1. INTRODUCTION

There are many seismic retrofit schemes for structural walls and columns which are main seismic as well as vertical load resisting components. It is traditional to construct additional concrete and/or steel structural walls or braced steel frames and anchor them to existing RC walls or frames. This type of strengthening method has a long history and is considered as one of the most common methods. However, it necessitates heavy construction effort. Since fiber reinforced polymers (FRP) began to play an important role in the civil engineering in 1990's, carbon fiber reinforced polymer (CFRP) has been used on columns first and then on structural walls to increase the shear strength and confinement. CFRP retrofit procedures are much easier compared to steel jacketing and steel bracing, but the surface needs to be smoothened and a part of the concrete needs to be taken to avoid sharp corners. The epoxy resin used with CFRP is sometimes too stimulus for construction workers and residents of buildings. Although it has superior seismic performance and ease of construction, CFRP has not been necessarily considered as the best retrofit materials.

FRP with low Young's modulus (SoftFRP) was developed in late 1990's and early 2000's. They were manufactured from relatively economical materials like polyacetar [1] or polyester [2] to substitute expensive CFRP in the beginning. FRP with high Young's modulus like CFRP may fracture when it experiences large tensile strain at cracks. However, it was found that a large deformation capability of SoftFRP was more effective to strengthen concrete structures since it is highly resistant to the local concentration of tensile strain at cracks.

Super Reinforcement with Flexibility (SRF) was developed as a construction material in 1999 and considered as one of SoftFRP's. Its typical mechanical properties are compared with those of CFRP and a mild steel plate in Table 1. Young's modulus is 1/40 of that of CFRP or ordinary steel. The tensile strength is 1/35 of CFRP and the strain at the tensile strength is ten times larger. The properties on the tensile strength and strain are similar to those of an ordinary mild steel plate. It should be noted that SRF costs 2/3 of CFRP and much easier to purchase locally. The research on SRF was first published regarding retrofit of reinforced concrete columns in 2000 [2]. Since then, retrofit on RC columns has been studied extensively [3]. Studies on the use of SRF to retrofit structural walls have just begun recently [4][5][6].

This study explains the experimental works on structural walls and columns strengthened with SRF. The effect of SRF on the enhancement of shear strengths and confinement are explained. The resisting mechanism of members strengthened with SRF is discussed to understand the behavior of SoftSRF.

Table 1 Typical mechanical properties of SRF, CFRP and steel plate

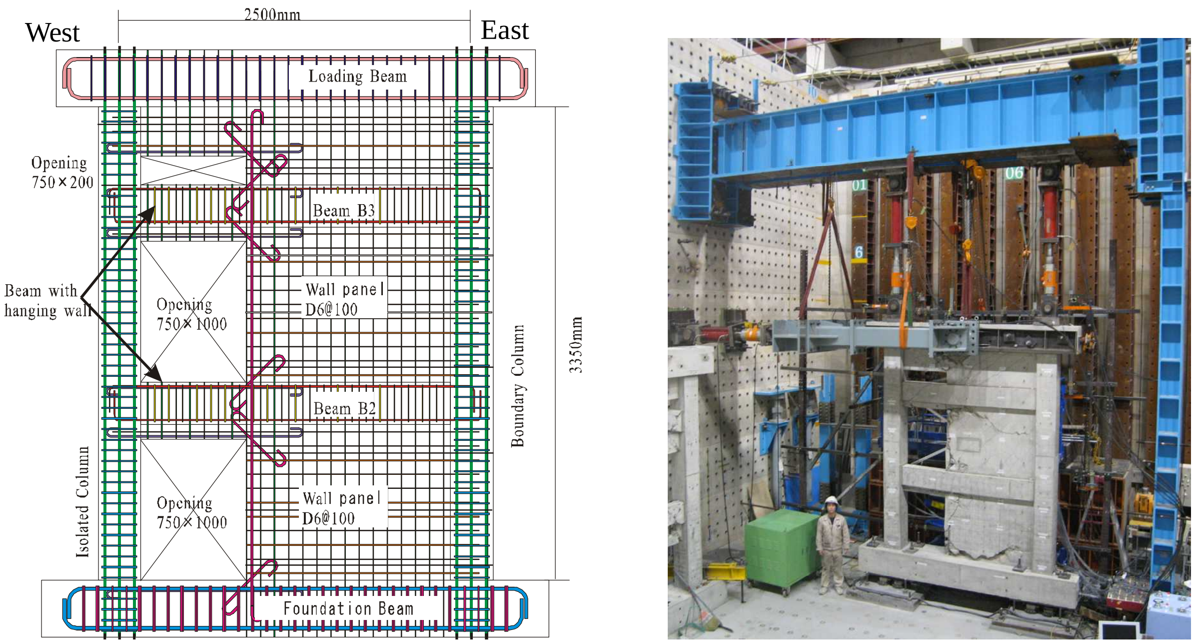
Material	Young's modulus (GPa)	Yield strenth (MPa)	Tensile strength (MPa)	Strain at tensile strength (%)
SRF (SRF465)	6.3	63	580	17
CFRP	235	* -	3400	1.5
Steel plate (SS400)	220	325	400	20

* CFRP is basically linear elastic and does not yield.

2. EXPERIMENT ON STRUCTURAL WALLS

2.1 Experimental setup

Two identical structural wall specimens were constructed with eccentric openings as shown in Figure 1. One specimen without any strengthening is designated as L1 and the other specimen strengthened with SRF sheet is designated as L4. A single layer of SRF sheet was applied on the south face of the wall and anchored to the north face as shown in Figure 2. The beams of the second and third floor (B2 and B3) next to the openings were also strengthened with a single layer of SRF. The specimens were designed as a lower portion of a six-story structural wall. Materials used commonly for both specimens are listed in Table 2 and mechanical properties of materials are listed in Table 3. Polyurethane adhesive was used for placing SFR on the concrete surface.

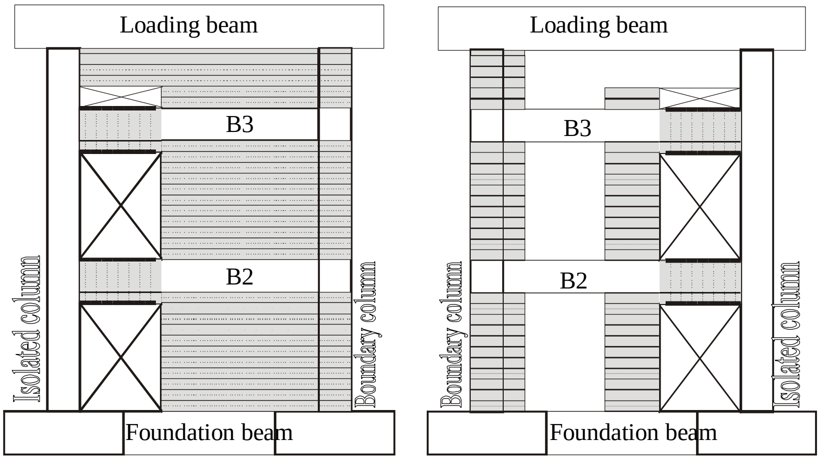


(a) Configuration and reinforcement arrangement of L1 and L4 (b) Loading system

Figure 1 Specimen and loading system (Unit: mm)

The lateral load was applied to the loading beam as shown in Figure 1(b) and the drift at the midspan of loading beam was controlled. The loading protocol was two cycles each at drift angles of 0.05%, 0.1%, 0.25%, 0.5%, 0.75%, 1.0%. The vertical load was applied to the top of each column based on Eq. (4) so that the contraflexure point was 2500 mm above the foundation beam. The detail of the experiment may be referred to the companion paper [7].

$$N_e = 0.42Q + 244kN \quad and \quad N_w = -0.42Q + 244kN \tag{1}$$



(a) South face (b) North face

Figure 2 SRF configuration placed on L4

Table 2 Section size and reinforcing bars in common

Member	Section size	Longitudinal bar		Shear reinforcement	
		Type	Steel ratio	Type	Steel ratio
Boundary column	300×300mm	8-D19	2.55%	2-ϕ10@75	0.63%
Beam	200×300mm	2-D13	0.47%	2-ϕ6@100	0.32%
Wall	t=80mm	D6@100(Staggered) 0.4% in both vertical and horizontal shear reinforcement			

Table 3 Mechanical Properties of Reinforcement

(a) Reinforcing bars for L1

Type	Yield strength (MPa)	Maximum strength (MPa)	Young's modulus (GPa)
D6	425	538	204
D10	366	509	180
D13	369	522	189
D16	400	569	194
D19	384	616	183
ϕ10	985	1143	197
Separator	1260	1461	759

(b) Reinforcing bars for L4

Type	Yield strength (MPa)	Maximum strength (MPa)	Young's modulus (GPa)
D6	425	538	204
D10	352	496	186
D13	362	529	188
D19	411	605	189
D25	387	541	194
φ10	1033	1221	204

(c) Concrete

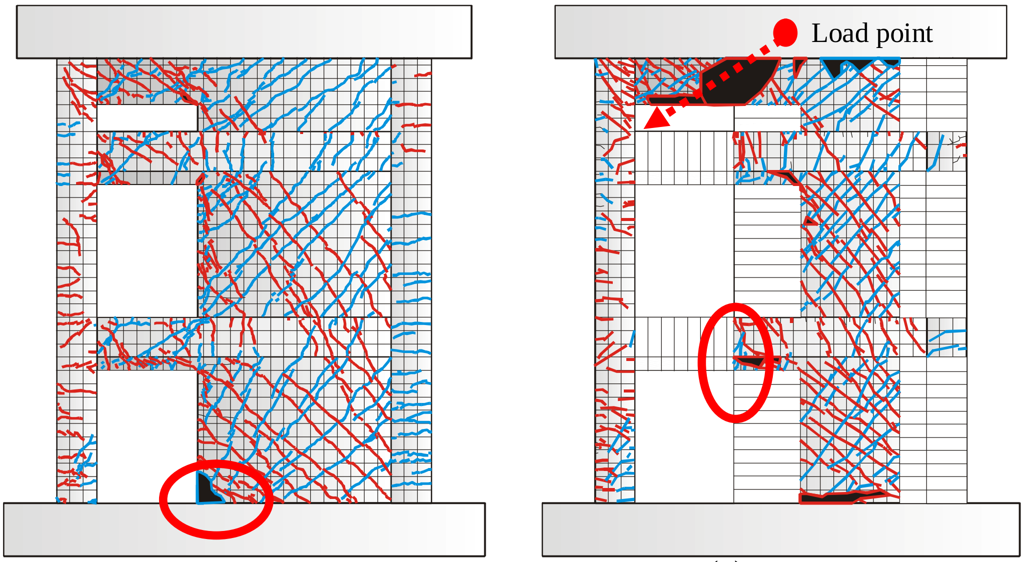
Specimen	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
L1	28.9	-	26.0
L4	26.8	2.3	20.4

(d) SRF Sheet

Width (mm)	Thickness (mm)	Young's modulus (MPa)	Tensile strength (MPa)	Strain at failure (%)
100	2.5	5800	400	10

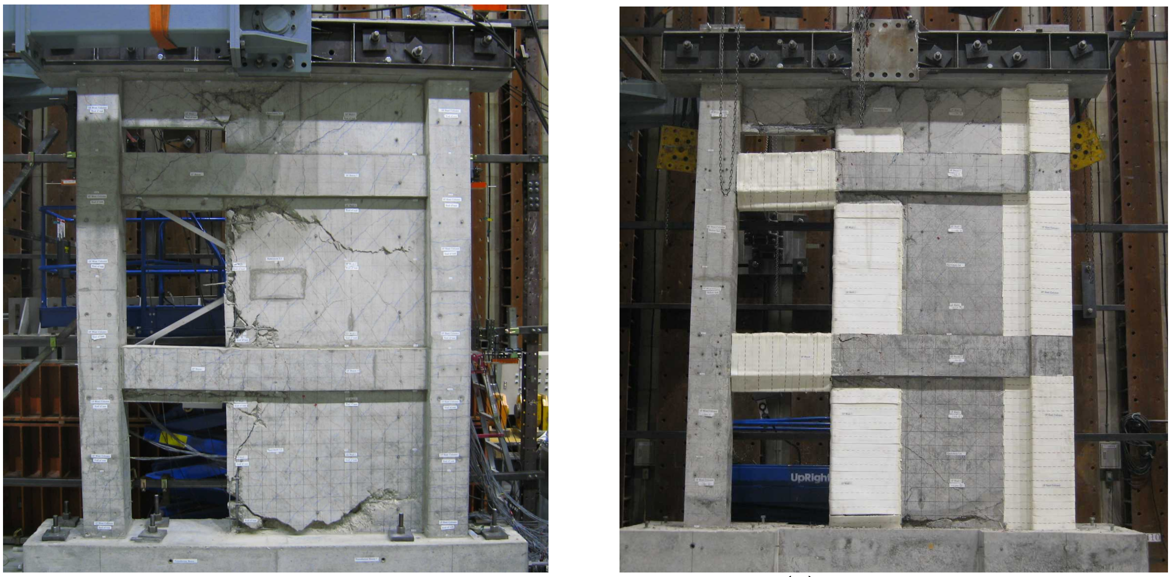
2.2 Experimental results

Crack distributions are shown in Figure 3 and damage after loading test is shown in Figure 4. The first shear crack of L1 was found at the first floor wall panel at drift angle (R) of +0.04%, and the number of cracks kept increasing till R=0.5%. Then the vertical reinforcement buckled at the wall base of the first floor at the region enclosed by a circle. The concrete started to spall locally from this drift angle. Then the shear sliding failure along the foundation beam took place along the wall base at R=+1.5% and the lateral load dropped suddenly. L4 strengthened with SRF sheet had the initial shear cracks at R=+0.05% and the number of cracks increased until R=0.5%. At the part of B2 enclosed with a circle in Figure 3(b), the flexural crack opened by large amount and the maximum load was reached at R=0.68% in the positive direction. Peak load in negative direction was reached when the shear failure occurred at the third floor wall panel since the force path, shown in dotted arrow in Figure 3(b), was not secured due to a opening. In positive direction, the force path was secured and the wall resisted the external force until R=1.25%. Degradation of load carrying capacity in positive direction started at R=1.25% at which the sliding shear failure occurred just below the loading beam.



(a) L1 (b) L4

Figure 3 Crack distribution at R=0.75%

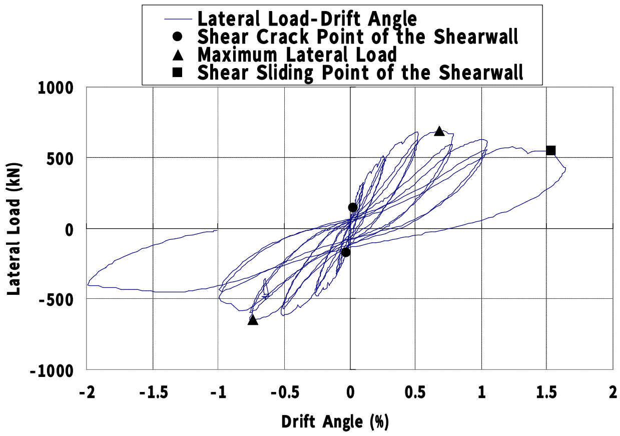


(a) L1 (b) L4

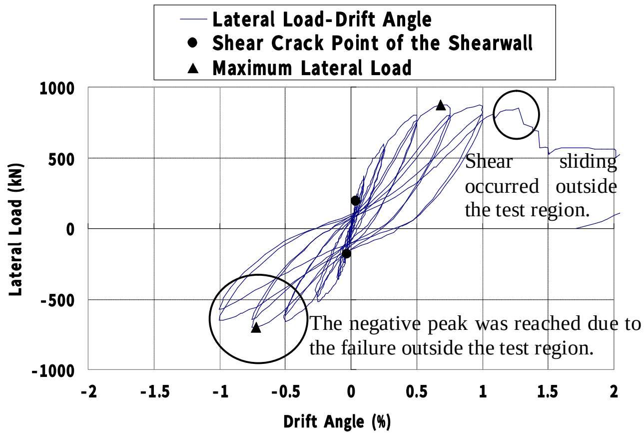
Figure 4 Photographic view after the loading test

Lateral load – drift angle relations are shown in Figure 5 and the initial stiffness and shear strengths are summarized in Table 4. Test results of N1, which had no openings nor strengthening, is also listed in the table as a reference. It is clear that SRF did not affect the initial stiffness but affected the shear strengths. Since the degradation of the shear strength from the positive peak to R=+1.3% was gentler than that of L1, it may be said that the confinement of SRF increased the ductility of the structural wall.

When the shear strength of L4 was computed, the effect of SRF was taken into account by adding the equivalent amount of shear reinforcement steel to the equation. The equivalent amount of steel was determined so that the steel at yielding carries the same magnitude of force which a given amount of SRF carries at the stain of 0.57%. The computed and experimental shear strengths in Table 4 agree well in the positive direction and the employed equation is considered reasonable.



(a) L1



(b) L4

Figure 5 Lateral load – drift angle relations

Table 4 Summary of loading test results

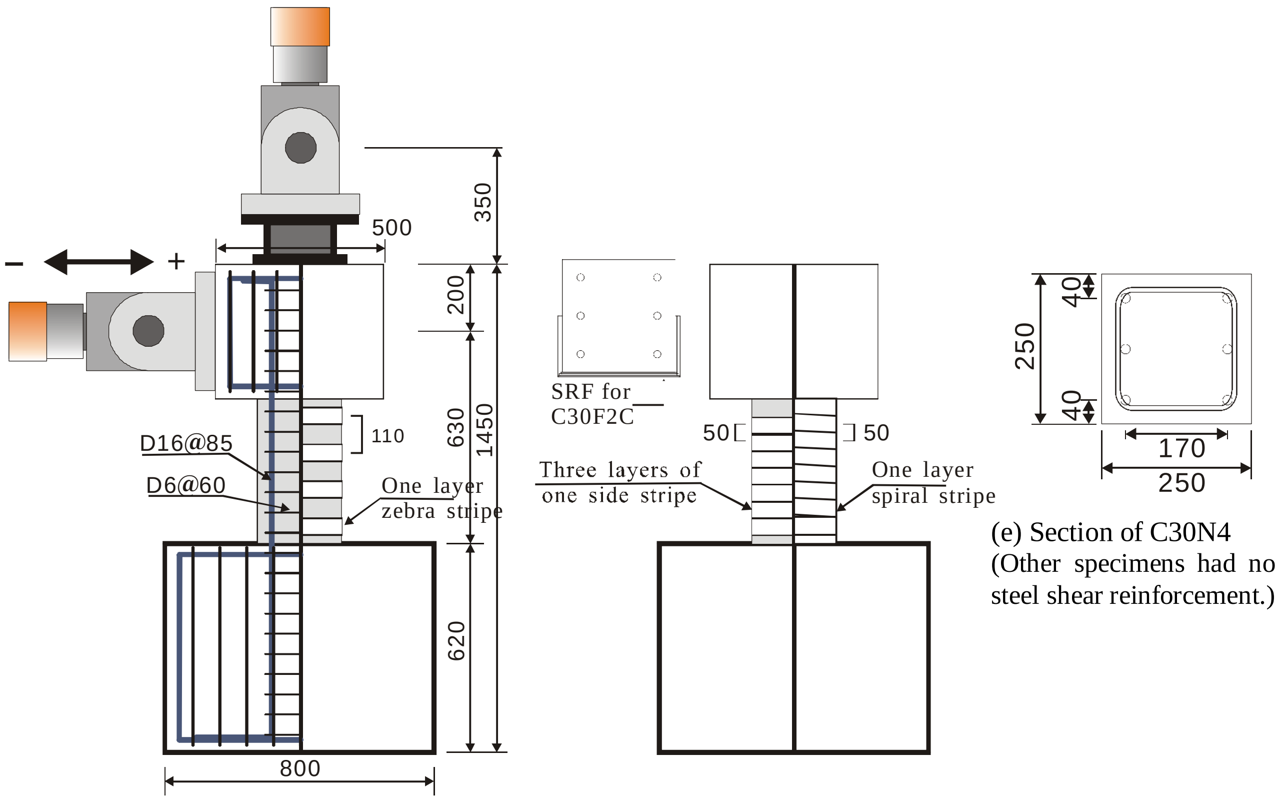
Specimen	Positive direction				Negative direction			
	Maximum load Qe, (kN)	**Computed strength Qc, (kN)	Drift angle (%)	Initial stiffness (10^5kN/rad)	Maximum load Qe, (kN)	Computed strength Qc, (kN)	Drift angle (%)	Initial stiffness (10^5kN/rad)
*N1	1179	1120	0.48	16.0	-1039	1120	-0.42	13.4
L1	686	633	0.68	5.9	-649	633	-0.74	6.7
L4	873	904	0.68	5.7	***(-705)	904	-0.73	5.6

* N1 is a specimen without any openings. ** Qc was computed from Ref. [8] considering the reduction factor due to openings.
*** The value is not considered as the real maximum since the wall panel at the third floor, which is outside the test region, failed.

3. EXPERIMENT ON COLUMNS

3.1 Experimental setup

An experiment was also conducted using five RC column specimens. Their configurations and test variables were the existence of steel hoop and amount of SRF as shown in Figure 6 and Table 5. Concrete had compressive strength of 27.4 MPa and Young's modulus of 19.6 GPa. Mechanical properties of steel and SRF are listed in Table 6. Axial force was kept constant at 30% of the axial compressive strength of the column and the lateral load was cyclically applied twice each at the pre-selected drift angles. The loading protocol for C30N0 and C30N4 differed from that of other three specimens as can be seen in Figure 7. The detail of the loading system may be referred to the companion paper [9].



(e) Section of C30N4 (Other specimens had no steel shear reinforcement.)

(a) C30N4 (b) C30F2R (c) C30F2C (d) C30F4

Figure 6 Specimen configurations (Unit: mm)

Table 5 Summary of test variables and test results

Specimen	Shear reinforcement		Computed strength		Experimental strength	
	Mild steel hoop	SRF	Shear Qvu (kN)	Flexure Qmu (kN)	Positve +Qe (kN)	Negative -Qe (kN)
C30N0	None	None	80*1		129	-
C30N4	D6@60 (p_w=0.0042)	None	137*1		119	-
C30F2R	None	One-layer zebra stripe (p_{wef}=0.0025)	94*2	125	124	-136
C30F2C	None	Three layers of one side stripe (p_{wef}=0.0025)	94*2		132	-132
C30F4	None	One layer spiral stripe (p_{wef}=0.0050)	145*2		133	-133

*1 Based on the AIJ standard [10]. *2 Based on SRF specifications [11] *3 p_{wef} is the equivalent reinforcement ratio

Table 6 Mechanical properties

(a) Steel reinforcing bar

Bar type	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
D6	425	538	204
D16	320	478	182

(b) SRF

Sheet type	Width thickness (mm)	Effective Young's modulus (MPa)	Fracture strength (MPa)	Strain at Fracture (%)
SRF450	50×4	5800	400	10

3.2 Experimental results

Lateral load – drift angle relations are shown in Figure 7 and the peak values in positive and negative directions are listed in Table 5. The computed shear capacities were smaller than the flexural capacity for three specimens but all five specimens seemed to have reached the flexural capacities. This is because a large amount of the shear force was resisted by the horizontal component of the inclined axial force trajectory from loading point to the neutral axis at the column base since the column was stocky. Hence Figure 7 shows the confining effect of SRF on the plastic hinge region.

C30F2C had three layers of SFR only on one side of the section and SRF was extended to the adjacent two sides for anchorage. Its lateral load – drift angle relation was similar to that of C30F2R until the concrete started to fail in shear at R=2%. C30F2R showed the steady and slow degradation of lateral load carrying capacity until the end of the loading test. C30F4 had double amount of SRF compared to C30F2C and C30F2R and hence the degradation of load carrying capacity was much slower than that of C30F2R. C30F4 carried larger lateral load than the other four specimens for a given drift angle as can be seen from the envelope curves in Figure 7. It can be seen that SRF effectively confined the core concrete at the plastic hinge region to greatly enhance the ductility.

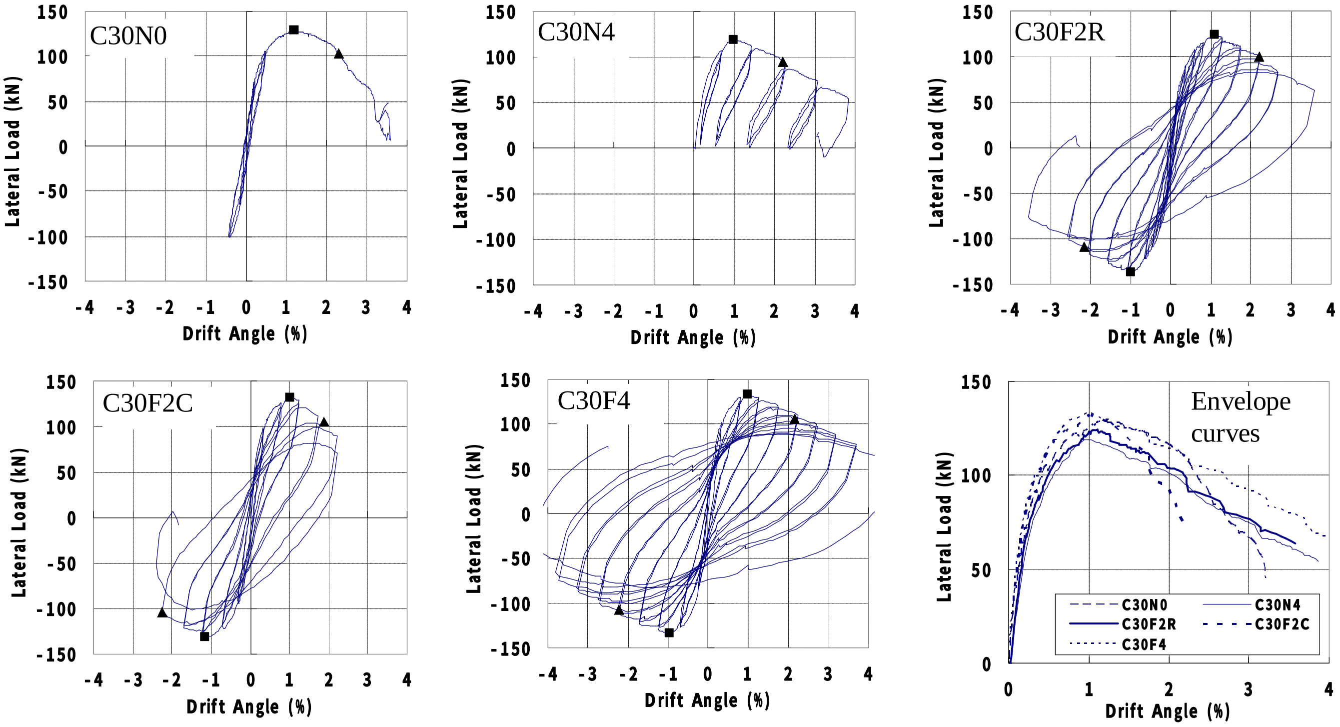


Figure 7 Lateral load – drift angle relations and their envelop curves

4. DISCUSSIONS

Shear strength of the structural wall (L4) in the positive direction was enhanced by 27%. This can be explained that SRF worked as additional horizontal reinforcement. However, it is interesting to consider reasons behind it. Both SRF and polyurethane adhesive have low stiffness but high deformation capability. With SRF attached on concrete surface, cracks did not concentrate locally but rather distributed evenly over wall panels, and consequently the number of cracks increased for a given drift. Since the number of cracks increased, the width of cracks decreased. The cracks with smaller width made the aggregate interlock more effective resulting in the enhancement of shear capacity. SRF also alleviated deterioration of the load carrying capacity by preventing the spalling of concrete. Even after the concrete of the compression strut failed in compression, crushed concrete stayed in the original position since SFR held it. This kept the shear resisting mechanism continue to work even if concrete crushed in the compression strut. Consequently, the degradation after the peak became gentler.

Confining effects of SRF was also confirmed from the experiment on column specimens. In addition to the increase of moment capacity, the ductility after the capacity was greatly enhanced. This confining mechanism is very similar to other FRP materials. Even if concrete failed in compression, concrete was confined within the enclosed SRF and did not come out from the SRF enclosure. Hence the sudden drop of load was avoided.

In addition to the force resisting mechanisms stated above, SRF has a function to relieve stress concentration due to its large deformation capability. The corners of the RC members do not have to be round like they should be when using CFRP, which is sensitive to sharp corners. FRP can be also applied to large bridge columns, brick-walls and lumber structures as well for its design flexibility, ease of handling at construction and low price.

5. CONCLUSIONS

Fiber reinforced polymers with low Young's modulus was used to retrofit RC structural walls and RC columns in experiments. Their large deformation capability greatly improved seismic performance of structural walls and columns compared to the carbon fiber reinforced polymers and also relieved stress concentration. It is very easy to handle fiber reinforced polymers with low Young's modulus as a construction material. The fiber reinforced polymers with low Young's modulus will greatly improve the current construction practice.

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