Shear Properties of CFRP Unit and Unit Walls Bonded with Epoxy Resin Adhesive

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Carbon Fiber Reinforced Polymer (CFRP) units and wall bonded with the units have been developed for one of the seismic retrofit technologies for reinforced concrete frames. They have good performance in in-plane shear strength for its thinness and lightness. The units are bonded together with epoxy resin adhesive. In the case of high performance joint, splice plates are bonded along joints. Experimental program, which consisted of tensile lap-shear test, unit shear test, joint shear test, and wall shear test, was conducted. The parameters of the wall shear test were bond patterns and with/without splice plates. The average shear strength of units was 801kN/m. The maximum shear load was 697 kN/m for the running bond wall with splice plates. The value was sufficient for earthquake-resistance shear wall. On the other hand, the adhesive shear strength for CFRP/CFRP by the tensile test was 15.1 N/mm^2, 8.8N/mm^2 for joint test, and 3.5 N/mm^2 for the stack bond wall by wall shear test. The decreases were considered due to nonuniformity of shear stress on the adhesive surface and stress concentration at the corners of the units in the walls.

Keywords : *Shear Experiment, CFRP unit, Shear wall, Epoxy resin adhesive*

1. INTRODUCTION

New infill blocks consisting of the Carbon Fiber Reinforced Polymer (CFRP) units have been developed for one of the seismic retrofit technologies for reinforced concrete frames. So called CFRP unit wall, infilled with these CFRP units, has a good performance in in-plane shear strength for its thinness and lightness. The shape of the unit is a rectangular block with 100 mm in thickness. The weight of the wall is about 41 kg/m^2. The units are bonded together with epoxy resin adhesive. In the case of high joint strength, splice plates are bonded along joints. A RC frame infilled with CFRP unit wall is illustrated in Fig.1. This construction features less noise and less dust because of lightness and easy installation.

Experimental program, which consisted of tensile lap-shear test, unit shear test, joint shear test, and wall shear test, was conducted. The parameters of the wall shear test were bond patterns and with/without splice plates. This paper shows the shear properties of the CFRP unit and the unit walls. Furthermore the difference of adhesive strength between the results of the lap-shear test and the other tests is discussed by means of Finite Element Analysis (FEA).

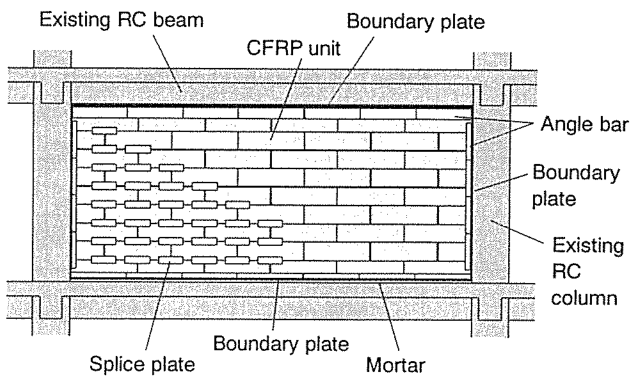


Fig.1 RC frame infilled with CFRP unit wall

2. CFRP UNIT AND MATERIAL PROPERTIES

Fig.2 shows the illustration of the CFRP unit. The standard shape of the unit is a rectangular box with dimensions of 100 mm in thickness, 300mm in height and 900mm in length. The units are formed by RTM (Resin Transfer Molding). It has CFRP skin plates outside which is reinforced carbon fibers in ±45 degree from the horizontal direction. Units are bonded together with epoxy resin adhesive. In the case of high joint strength, splice plates are bonded along joints.

Table 1 shows the lamina properties, Table 2 lamination layers of the skin plate. The skin plate consists of the five layers bound with vinylester matrix. The first and the last layers are Glass Fiber (GF) mat, the second and forth are Carbon fiber, and the center layer is unidirectional GF. The theoretical properties of the laminated skin plate show Table 3.

In this study, the same product of epoxy paste adhesive was used in each test. Table 4 shows the adhesive properties.

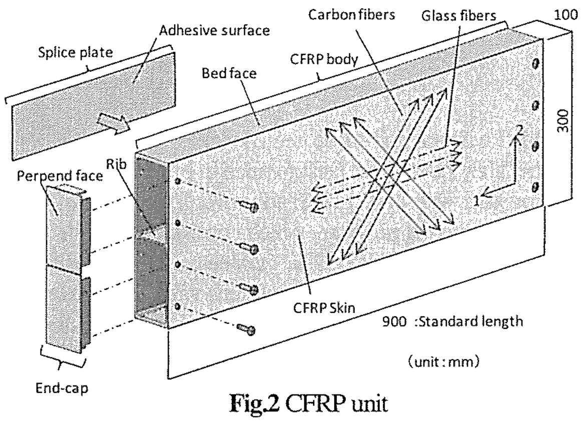


Fig.2 CFRP unit

Table 1 Lamia properties

Layer Material	E_1, E_2 kN/mm^2	G_{12} kN/mm^2	ν_{12}
CF layer	72.0	5.5	0.067
GF_Mat layer	12.6	4.8	0.304
GF_UD layer	41.0	4.6	0.253

(Subscript) 1:axis of member, 2:transevesrse axis of member

Table 2 Lamination layers of skin plate

Layer Sequence	Layer Material	Effective thickness (mm)	angle*
1	GF_Mat layer	0.3	0°
2	CF layer	1.2	±45°
3	GF_UD layer	1.0	0°
4	CF layer	1.2	±45°
5	GF_Mat layer	0.3	0°
	total thickness	4.0	

* Degree from horizontal direction

Table 3 Lamination properties of skin plate (calculations)

E_1	E_2	G_{12}	Tensile Strength	Compressive Strength	Shear Strength
22.7	19.9	22.4	520	600	196

(Units) E_1, E_2, G_{12}: kN/mm^2, Strength: N/mm^2

(Subscript) 1:axis of member, 2:transevesrse axis of member

Table 4 Adhesive properties* (specified values in catalog)

E	G	ν	Tensile Strength	Compressive Strength	Shear Strength
2300	885	0.3	≧20	≧45	≧15

* Adhsive: Konishi Bond E258 (Units:N/mm^2)

3. EXPERIMENTAL PROGRAM

The experimental program consisted of the four types of tests as follows.

(1)Tensile lap-shear test: This test determines strength of adhesives for steel/steel, steel/CFRP, CFRP/CFRP using the test method like ASTM D5868.

(2)Unit shear test: This test determines shear response and shear strength of the unit.

(3)Joint shear test: This test determines shear strength of unit joint. Two types of specimens were conducted, one of which is bonded face to face of units and the other additionally bonded splice plates.

(4)Wall shear test: This test determines shear strength of wall. Three types of specimens varied with bond patterns and with/without splice plates, were conducted.

4. TENSILE LAP-SHEAR TEST

4.1 Specimens

Table 5 shows the types of the specimens. Fig.3 shows the dimension of the specimen. Three types of adhereds consisted of steel/steel, steel/CFRP and CFRP/CFRP were tested. The adhesive surface of steel was shot blast finishing, CFRP sandpaper (#100) finishing. The thickness of adhesive was about 0.2 mm which was set by spacer of masking tape.

4.2 Test Procedure

The test specimens are placed in the grips of a universal testing machine and pulled like ASTM D5868. The environmental temperature was 18℃ to 20℃ during the tests.

4.3 Results

(1) Failure modes

Fig.4 shows the adhesive interfaces. The failure mode of specimen S/S was cohesive failure, specimen C/S mixed of cohesive failure and interface failure, and specimen C/C mixed of interface failure and substrate failure.

(2) Shear strength of adhesive

Fig.5 shows the adhesive shear strengths. The average of adhesive shear strength of specimen S/S was 20.0 N/mm^2, specimen C/S 20.3 N/mm^2 and specimen C/C 15.1 N/mm^2. The strength of specimen C/C was 25% decreased by comparison with specimen C/S. It is considered due to the substrate failure.

Table 5 Types of specimens

Symbol	Adherends	Thickness of Adherend (mm)	Thickness of Adhesive (mm)	N
S/S	Steel／Steel	4.5／4.5	0.2	3
C/S	CFRP／Steel	2.8／4.5	0.2	3
C/C	CFRP／CFRP	2.8／2.8	0.2	3

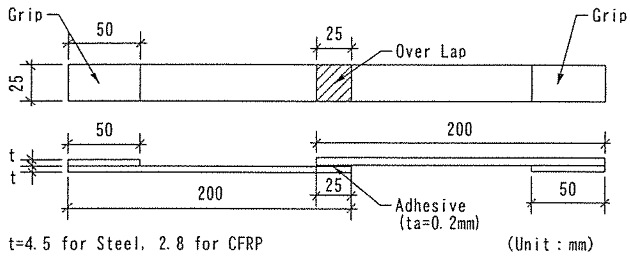


Fig.3 Configurations of lap-shear specimen

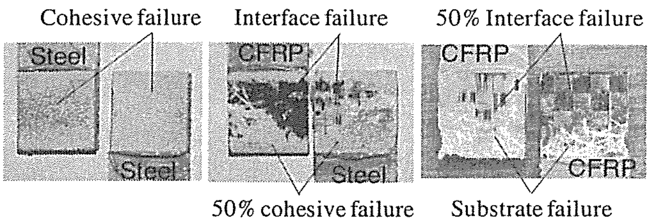


Fig.4 Adhesive interface

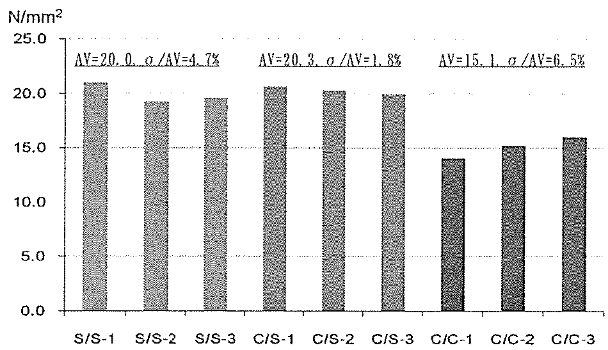


Fig.5 Adhesive shear strengths

5. UNIT SHEAR TEST

5.1 Specimens and Test setup

Fig.6 shows the configuration of the specimen for unit shear test. The properties of the skin were described by Table 1,2 and 3. The effective thickness of the skin was 4.0mm.

The specimen consisted of test part and constraint part. The test part where was at the center was with dimensions of 80 mm in thickness, 300mm in height and 900mm in length. The constraint part was the extended skins so as to set up by the bearing bolts. The effective thickness of the extended skin was 10 mm.

The experimental parameter is the depth of the end cap insert. The end caps work for restraining the buckling of the skin plate. The depth of 25mm is called specimen U-1, 50mm U-2.

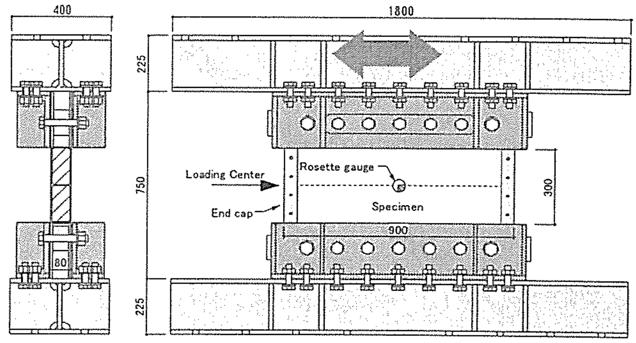


Fig.6 Configurations of unit specimen

5.2 Test Procedure

The specimens were tested under cyclic horizontal load with hydraulic jack. The loading program is controlled by the deformation angle of ±0.2%rad, ±0.25%rad, ±0.3%rad, ±0.4%rad, ±0.5%rad, ±0.67%rad and ±1.0%rad.

The deformation of unit was measured by displacement potentiometers where set at the upper and lower of unit and by a strain rosette gauge where set at the center of the unit.

5.3 Results

(1) Failure modes

Fig.7 shows the failure mode of a specimen. Shear bucklings were observed in both specimens. It was noticed that the end caps of both specimens were effective to prevent propagations of shear buckling waves.

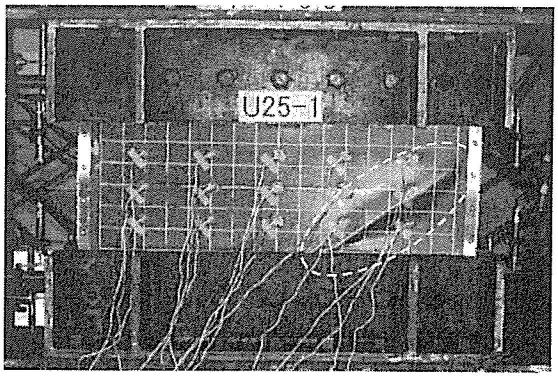


Fig.7 Shear buckling of unit

(2) Relationship between shear force and shear strain

Fig.8 shows the relationships between shear force and shear strain measured by the rosette gauge. The characteristics of the relationships are very linear until the loads reached to the peaks. However the shear force was rapidly decreasing after the bucklings. The stiffness of both specimens was almost the same.

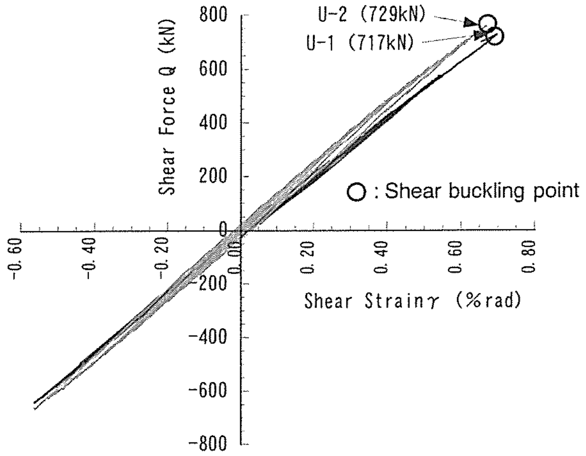


Fig.8 Shear force vs. shear strain of all specimens

(3) Shear buckling strength

Table 6 shows the results of the unit shaer test. The average strength at 0.4% shaer strain was 481kN (extrapolation: 534kN/m), one at the shear bucklings was 723kN (extrapolation: 803kN/m). The average shear strain at the shear bucklings was 0.68% rad.

Table 6 Results of unit shear test

Speci-men	0.4%rad strength	shear buckling strength	γ	0.4%rad strength per unit length	shear buckling strength per unit length
	kN/unit	kN/unit	%rad	kN/m	kN/m
U-1	482	717	0.65	536	797
U-2	480	729	0.70	533	810
Avg.	481	723	0.68	534	803

6. JOINT SHEAR TEST

6.1 Specimens

Fig.9 shows the configuration of joint test specimen. Two types of specimens were tested. Two piece of the half unit of specimen U series were bonded with epoxy adhesive resin described by Table 4. Specimen J-0 was the normal joint specimen bonded by face to face of units with adhesive. Specimen JS-1 was the same of specimen J-0 but additionally bonded with splice plates.

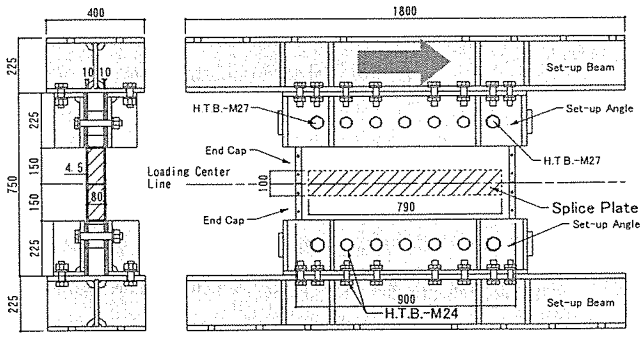


Fig.9 Configuration of joint test specimen

6.2 Test Procedure

The specimens were tested under horizontal one-way load with a hydraulic jack. The deformation of unit was measured by displacement potentiometers where set at upper.

6.3 Results

(1) Failure modes

Specimen J-0 was broken at the joint shown as Fig. 10. From the observation of the adhesive interface, the failure mode was substrate failure of GF-mat layer. On the other hand, JS-1 was not broken at the joint but the shear buckling of the unit.

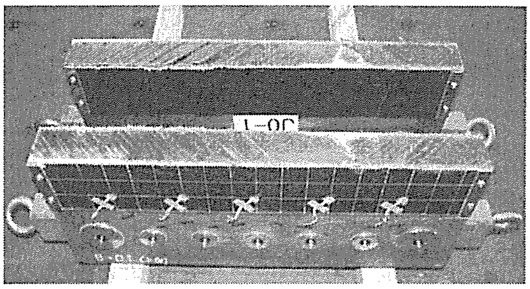


Fig.10 Adhesive Interface of J-0

(2)Shear strength of joints

Table 7 shows the results of the joint shaer test. The maximum load of specimen J-0 was 631 kN, the average shear strength divided by the adhesive area (80mm×900mm) was 8.8N/mm^2. On the other hand, the maximum load of specimen JS-1 was 883 kN. The restraint of the splice plates of specimen JS-1 should conduce a little high strength compeared with specimen U series.

Table 7 Results of joint shear test

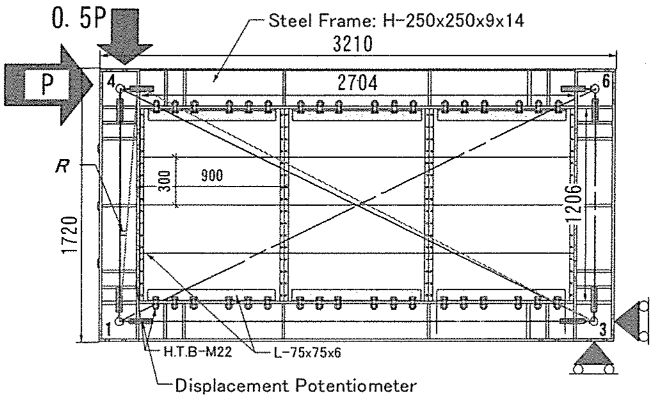
Specimen	Failure Mode	Strength	Shear stress
		kN	N/mm^2
J-0	Substrate Failure	631	8.8
JS-1	Buckling	883	

7. WALL SHEAR TEST

7.1 Specimens

The units with 100mm in thickness were used in this experiment. The material properties were the same of the unit and joint shear tests.

Fig.11, 12 and 13 show the configurations of the specimens. Table 8 shows the experimental parameters. The parameters were bond patters and joints. The bond patters were stack bond and running bond. The size of the infilled walls was 1200 mm in height and 2700 mm in length except the total thickness of adhesive. The unit arrangement for the stack bond wall consisted of 3 x 4 units. As for the running bond wall, half size units were installed at the four corners of the wall. Splice plates were attached to Specimen E and Y with adhesive in Fig. 12 and 13. The loading steel frame (H-250×250×9×14) was circumferentially arranged around the wall. The wall and steel frame were bonded with adhesive in addition to angle bars.



R: Story drift

Fig.11 Configurations of specimen N

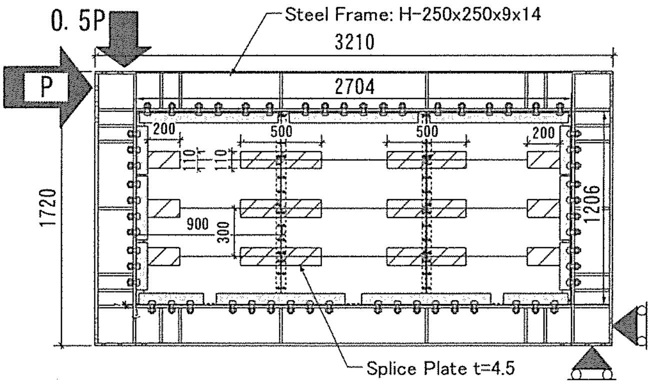


Fig.12 Configurations of specimen E

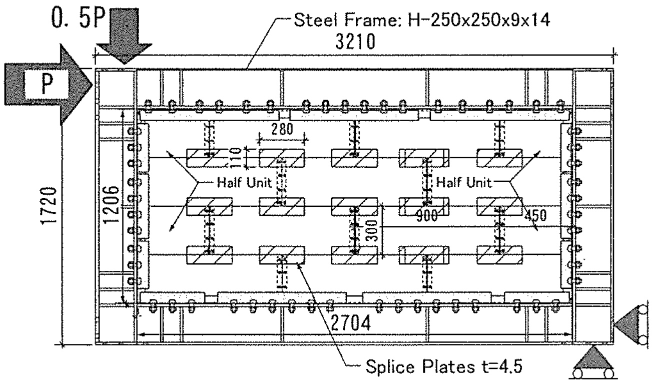


Fig.13 Configurations of specimen Y

Table 8 Outlines of specimens

Specimen	N	E	Y
Bond Pattern	Stack	Stack	Running
Total adhesive area along a horizontal joint (mm^2)	270,000	424,000	424,000
Designed joint strength* (kN)	1,620	2,544	2,544

*: used by τ_a=6.0N/mm^2

7.2 Test Procedure

The specimens were tested under cyclic diagonal load with four hydraulic jacks where set at the tops of the both steel columns. The loading program is controlled by the story drift of ±0.2%rad, ±0.25%rad, ±0.3%rad, ±0.4%rad, ±0.5%rad, ±0.67%rad, ±1.0%rad, ±1.33%rad and ±2.0%rad.

The deformation of the steel frame was measured by displacement potentiometers where set at the four corners of the frame along horizontal and vertical directions. The deformation of the units was measured by strain rosette gauges.

7.3 Results

(1)Failure modes

Fig.14, 15 and 16 show the final failure modes of each specimen. The solid lines are at the positive loadings, the dash lines negative loadings. The number in the figures indicates the occurred-order of the failure modes. The stepped diagonal cracks occurred in specimen N during the both positive and negative loadings. The stepped diagonal crack and unit shear bucklings occurred in specimen E at the same moment. As for specimen Y, first unit shear buckling occurred, next stepped diagonal crack.

(2) Relationship between shear force and story drift

Fig.17 shows the relationships between shear force and story drift of all specimens. The contribution of the steel frame strength, which is assumed as bilinear, is indicated as chain line.

The characteristics of the relationships are linear in both positive and negative directions until the loads reached to the peaks. However the shear forces were rapidly decreasing after the peaks. It is considered that the residual strength shown in Fig.17 should be given by the compression strut positioned the diagonal units.

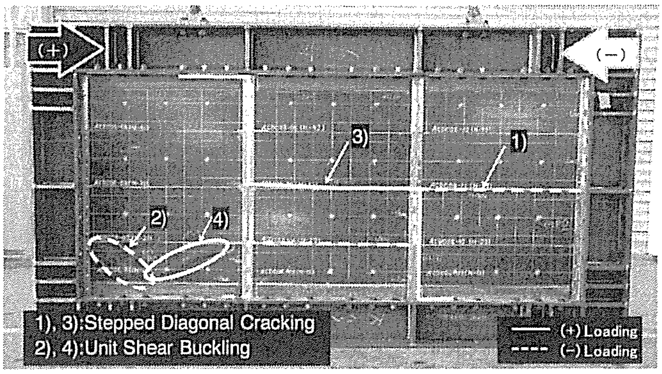


Fig.14 Failure mode of specimen N

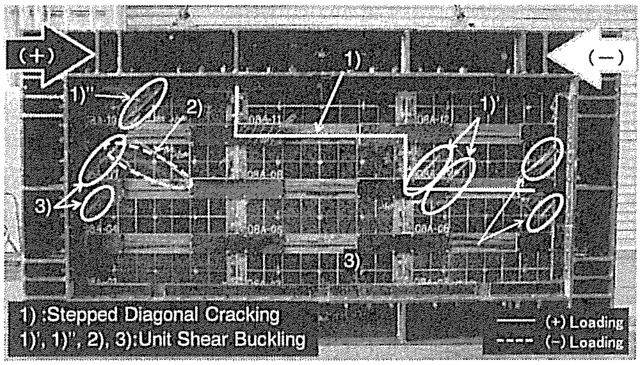


Fig.15 Failure mode of specimen E

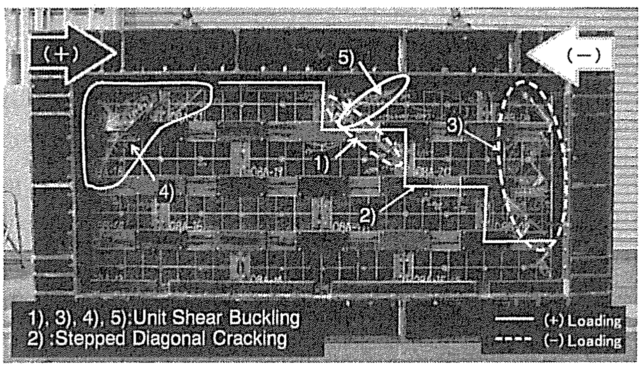


Fig.16 Failure mode of specimen Y

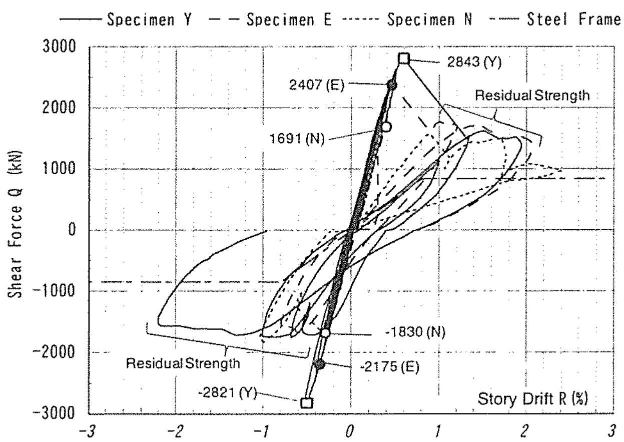


Fig.17 Shear force vs. story drift of all specimens

(3) Shear strength of CFRP unit walls

Table 9 shows the results for the specimens and the unit walls. In this experiment, each shear strains of the units at the peak load were uniformity in the wall plane. So the strength of CFRP unit walls is calculated as the product of the unit strength, the average strain and the horizontal number of units. Table 9 also shows the average shear stress divided by the face measure (100mm× 900mm×3).

With respect to the unit walls, the maximum shear strengths, the shear strengths for unit length and the average shear stresses were respectively 954kN, 353kN/m, 3.5N/mm^2 for specimen N, 1500kN, 555kN/m, 5.6 N/mm^2 for specimen E, and 1881kN, 697kN/m, 7.0 N/mm^2 for specimen Y. The values of specimen Y were twice as large as specimen N.

Table 9 Failure strength and shear strain

Specimen	Failure Mode	Specimen		CFRP Unit Wall				
		Q	R	Q_w	γ_{av}	q_w	τ_j	Ratio
		kN	%rad	kN	%rad	kN/m	N/mm^2	
N	J	1691	0.32	954	0.31	353	3.5	1.0
E	J&B	2407	0.45	1500	0.48	555	5.6	1.6
Y	B	2821	0.50	1881	0.61	697	7.0	2.0
	J	2843	0.58	1848	0.60	684	6.8	1.9

(Symbols)

J: Joint Failure, B: Buckling of unit

Q: Shear Force of whole Specimen, R: Story drift,

Q_w: Shear Force of CFRP unit wall,

γ_{av}: Average shear strain on units,

q_w: Shear Force of CFRP unit wall for unit length,

τ_j: Average shear stress of CFRP unit wall

8. DISCUSSION

8.1 Adhesive Shear Strength

The adhesive shear strength for CFRP/CFRP by the tensile tests was 15.1 N/mm^2, and 8.8N/mm^2 by the joint test in spite of the same failure mode. The reason of the decreasing is considered by Finite Element Analysis (FEA).

Fig.18 shows FEA model of the joint test. The FEA model is 3-dimensional. Solid elements are employed as adhesive, and shell elements as CFRP skin and steel beam. The mesh sizes of the solid element are 1.5 or 2mm×25mm×25mm, the shell element 25mm×25mm. All translation's degrees are constraint at the bottom flange, and the 2-direction's degree of freedom (DOF) is constraint at the top flange. Horizontal load of 1000kN is applied at the top steel beam.

Fig.18 shows the analytical results of the principle stress of adhesive. It shows that the amplitude of adhesive principle stress is maximum at the center and decreasing approaching to the ends of the unit. This is well-known as shear distribution in rectangular section.

Fig.19 shows the contour of principal stress on the adhesive joint plane. It is found out that the stress at the outside is high and decreasing approaching to the center. That is explained by the position of the skin plates outside.

Adhesive shear strength which is defined by load divided by adhesive area is generally decreasing according to widening adhesive area. The nonuniformity should lead to decrease the strength of the joint and the 'average' adhesive strength.

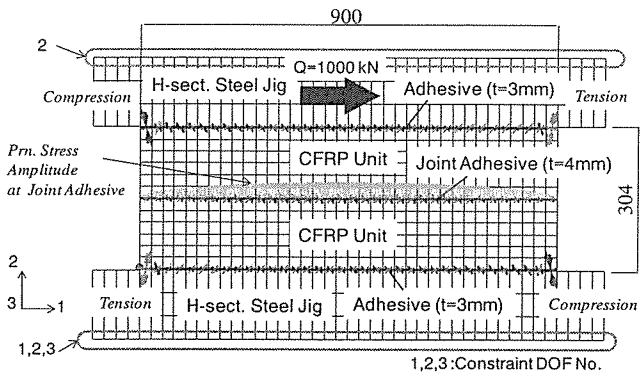


Fig.18 FEA model for joint test and result of principal stress in adhesive

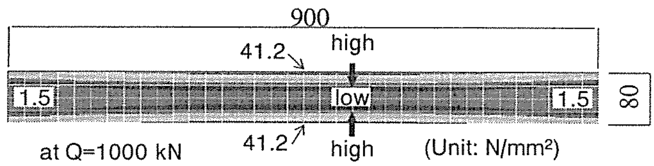


Fig.19 Contour of principal stress on joint adhesive plane

8.2 Reinforcing of Splice Plates and Bond Patters

Assuming the maximum strength of specimen N as 1.0, specimen E was 1.6, specimen Y 2.0. It is the fact that the splice plates largely improved the strengths of the walls.

The difference of adhesive shear stress for bond patterns is considered by FEA. Fig.20 shows the FEA model of the wall shear experiment. Beam elements are employed as the loading steel frame where are circumferentially arranged around the wall. Shell elements are employed as the units and adhesive to resist in-plane forces. A unit is divided by plane-shell elements with 8mm thickness (double of a skin thickness). Adhesive is divided by plane-shell elements. The effective thickness of adhesive is assumed 40mm (half with of adhesive area). The same mesh is adopted for both stack bond wall and running bond wall except for the element properties.

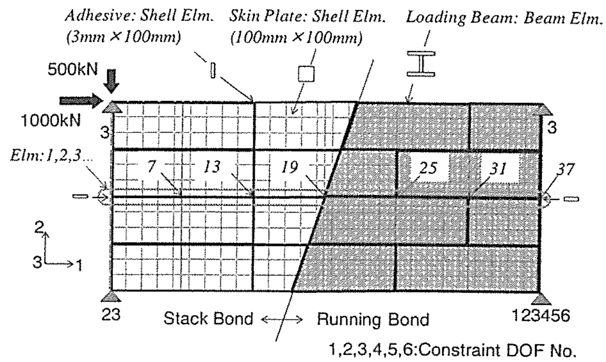


Fig.20 FEA model for wall test

Fig.21 shows the analytical result of the maximum principle stress along the center adhesive layer of the wall. X-axis indicates the numbers of elements along the layer. The solid line indicates stack bond wall, dashed line running bond wall. The generally shape of the curve is bow. This indicates that the wall resists in-plane shear like a uniform wall. Some peaks are appeared at the corners of the units in the both wall types. This suggests that the splice plates set at the corners of units are effective.

The peak value ratio of the element No.13 and 25 between stack bond wall and running bond wall is about 0.75. The experimental difference of the strength among them should be due to the stress concentration.

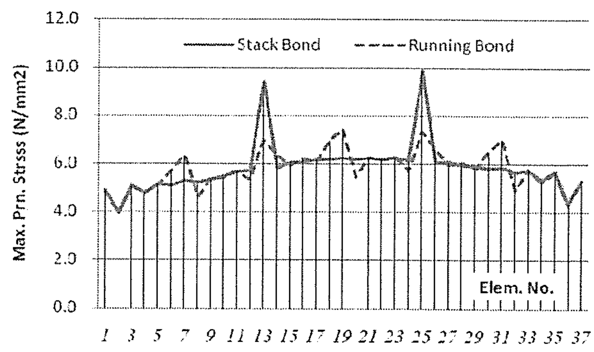


Fig.21 Maximum principle stress along adhesive layer

8.3 Capacity of CFRP Unit Wall for Retrofitting RC Open Frame

The strength of the CFRP unit wall with splice plates was from 555kN/m (5.6 N/mm^2) to 697kN/m (7.0 N/mm^2). Generally the capacities of retrofitting RC shear wall with 250mm thickness are from 420kN/m (1.7 N/mm^2) to 670kN/m (2.7 N/mm^2) [4], masonries from 1.5 N/mm^2 to 4.0 N/mm^2 [5),6)]. So the capacity of the shear strength for the CFRP unit wall is sufficient for retrofitting.

As for the characteristic of shear deformation, the story drift at peak shear strength of RC column is typically about 0.4% rad[4)]. As for the CFRP unit wall with splice plates, the maximum shear strain as well as peak strength was from 0.48% rad to 0.61% rad. So the deformation capacity of the CFRP unit wall exceeds the story drift at peak shear strength of RC column. On the other hand, no ductility of the CFRP unit wall should be sufficiently considered for the designs of retrofitting.

9. SUMMARY AND CONCLUSIONS

(1) The adhesive shear strength for CFRP-to-CFRP by the tensile test was 15.1 N/mm^2, 8.8N/mm^2 by joint test, and 3.5 N/mm^2 for the stack bond wall by wall shear test. The decreases were considered due to nonuniformity of shear stress distribution in the adhesive layer.

(2) The shear strength of the CFRP unit with 900mm long was 723kN (803kN/m) at 0.68%rad shear strain.

(3) From the results of the wall shear test, the maximum wall strengths of the stack bond wall were 954kN (353kN/m, 3.5N/mm^2), the stack bond wall with splice plates 1500kN (555kN/m, 5.6N/mm^2), the running bond wall with splice plates 1881kN (647kN/m, 7.0N/mm^2). These values with splice plates are same as the shear strength of the commonly used retrofitting RC shear walls. However, the strength was rapidly decreased after the peak.

(4) Splice plates were useful for preventing the failure of joints and increasing strength of unit walls.

(5) Running bond wall is superior to stack bond wall from the viewpoint of decreasing the stress concentrations which occurres at the corners of units.

(6) Above the results, the CFRP unit wall was useful for seismic retrofit device from the viewpoint of strength and story drift. Authors are going to represent the results of the shear experiments of reinforced concrete frame with CFRP units infilled walls afterward.

ACKNOWLEDGEMENT

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