SHEAR STRENGTHENING OF REINFORCED CONCRETE FRAMED SHEAR WALLS USING CFRP STRIPS

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ABSTRACT :
The seismic performance of reinforced concrete framed shear walls strengthening with Carbon Fiber Reinforced Polymer (CFRP) strips was quantitatively investigated in this study. The epoxy-bonded CFRP was placed in the diagonal positions in shear walls for shear strengthening. Six large-scale framed shear walls were tested. The results show that the seismic performance of low-rise shear walls strengthening with CFRP strips was significantly enhanced. However, the enhancement of mid-rise shear walls was insignificant. In addition, the improvement of the failure specimen directly retrofitted with CFRP strips was minor. This study is expected to generate both the scientific knowledge and the engineering method in the infrastructure.

KEYWORDS:
reinforced concrete framed shear walls, Carbon Fiber Reinforced Polymer(CFRP), large-scale structural test, numerical manifold method

1. Introduction

Seismic retrofit of old building has been an important research topic, especially after 1999 Chi-Chi earthquake, Taiwan. The urgent issue is to develop the easy construction and effective retrofit methods. Framed shear walls are extensively used as the components of earthquake resistance buildings. However, the conventional shear walls, which the reinforcements are in vertical and horizontal directions, frequently possess pinching effect in the load-displacement curves. Recently, Mansour and Hsu (2005) presented the experimental results of reinforced concrete elements under cyclic shear. They found that when the reinforcements are parallel to the principal directions of the element, there is almost no pinching effect in the load-displacement curves. These experimental results show that the orientation of reinforcements will affect the structural behavior of wall elements. The effects of layout of wall reinforcements on the structural behavior of framed wall sound an essential research.
Benjamin and Williams (1957) performed a series of tests on low-rise framed shear wall (Height/Width = 0.57) subjected to monotonic loading. They proposed a formula to predict the elasto-plastic load-displacement curves, and obtained the structural stiffness at various loads. Yamada et al. (1974) tested a low-rise framed shear wall (Height/Width =0.44) by monotonic loading. They proposed a displacement model, and studied the parameters of wall thickness and steel ratio of wall. Barda et al. (1976) presented tests on low-rise walls with boundary elements. They studied the parameters of vertical steel of boundary elements, horizontal and vertical steel of wall, and height to width ratio. Mau and Hsu (1987) investigated the shear behavior of framed walls and proposed a formula to predict the strength of walls. Mo and Kuo (1998) presented a displacement control test on small-scale framed shear wall subjected to reverse cyclic lateral loading. They studied the parameters of structural dimension and concrete strength. The experimental results were compared with solutions obtained by truss model and IDARC software, and a large deviation was found between test and analytical results.

The Carbon Fiber Reinforced Polymer (CFRP) has been recognized as a lightweight and high strength material, and it has been used in the retrofit of infrastructure recently. However, its seismic performance and effectiveness need further quantitatively investigated.
The seismic performance of reinforced concrete framed shear walls strengthening with CFRP strips was quantitatively investigated in this study. The epoxy-bonded CFRP was placed in the diagonal positions in shear walls for shear strengthening. Six large-scale framed shear walls were tested in this study.

2. Experimental System and Results

Figures 1 and 2(a) show the schematic configuration of the representative specimen and test setup. The displacement controlled cyclic lateral force (Figure 2(b)) was applied to the specimen. Each specimen was bolted at the steel foundation, which was then connected to the strong floor. The lateral displacements were measured by linear variable differential transformers (LVDT) and the force was measured by load cell. The experiment was displacement control, and its displacements were 1mm, 2.5mm, 5mm, 10mm, 15mm, 20mm, 25mm, 30mm, and 40mm, respectively. Each displacement was repeated twice the amount of loading. The measured force and displacement were collected by TDS-302 data logger. The experiment was monitored by the load-displacement curve.
Six specimens including three mid-rise framed walls (MW1, MW1C, MW1C2), and three low-rise framed walls (LW1-LW1R, LW1C, LW1Ca) were tested. Table 1 summarizes the properties of these specimens. The first letters M and L represent mid-rise wall and low-rise wall, respectively. The fourth letter C represents specimen retrofitted with CFRP. LW1R is the failure specimen directly retrofitted with CFRP strips. The fixed steel angles are closely contacted with the boundary columns for specimen LW1C, while there is 5cm separation between the steel angles and boundary columns for specimen LW1Ca.
The cross sections of column and beam are 25cm× 25cm and 40cm× 60cm, respectively. The steels of both column and beam are #6 steels, and the spacing of stirrup is 12.5cm. The widths of low-rise and mid-rise walls are 300cm and 200cm, respectively, while both heights are 200cm. Both the vertical and horizontal steels of wall are #3 steel with spacing of 25cm, and the thickness of wall is 8cm.
The crack patterns of all tested specimens are shown in Figure 3. The load-displacement curves of tested specimens are shown in Figure 4. Table 2 summarizes the experimental results. The energy absorption is defined to be the area bounded by the envelope of positive load-displacement curve. The ultimate displacement Δ_u is defined to be the displacement corresponding to the load descended steeply.
Figures 3(a) and 3(b) show the tested prototype specimens MW1 and LW1. It is found that the failure of mid-rise framed-wall is the combination of flexure and shear failure, while the low-rise framed-wall is shear failure. Figures 3(c) and 3(d) show the representative tested retrofitted specimens LW1R and LW1C, and Figures 4(c) and 4(d) show the load-displacement curves of specimens LW1R and LW1C, respectively. Because the cracks exist in the failure specimen, the load cannot transfer for the specimen directly retrofitted with CFRP. Referring to Figures 3 and 4, it is found that the improvement of the failure specimen directly retrofitted with CFRP strips was minor. Alternatively, referring to Figures 3 and 4, it is found that the low-rise framed shear walls strengthening with CFRP strips significantly enhance its seismic performance. Because the fixed steel angles closely contact with the boundary columns for specimen LW1C, the steel angles cut the boundary columns and induce the out of plane failure of wall. However, the separation of boundary columns and steel angles will avoid out of plane failure mode and induce larger energy dissipation.

3. Conclusions

This study presents the experimental research on the seismic performance of reinforced concrete framed shear walls strengthening with Carbon Fiber Reinforced Polymer (CFRP) strip subjected to reverse cyclic lateral loading. The conclusions from this research are followings:
1. The location of fixed steel angle affects the performance of retrofitted specimen. The steel angles closely contact with boundary columns will induce failure of the columns, and the ultimate displacement and ductility of specimen will reduce. Alternatively, the separation of boundary columns and steel angles will induce larger energy dissipation.

2. The low-rise framed shear walls strengthening with CFRP strips significantly enhance its seismic performance. However, the enhancement of mid-rise shear walls strengthening with CFRP strips was insignificant, and the improvement of the failure specimen directly retrofitted with CFRP strips was minor.

3. The performance of retrofitted specimen is significantly reduced when the inclined angle of CFRP exceeds 100 degrees. The inclined angle is proposed to between 80 and 100 degrees.

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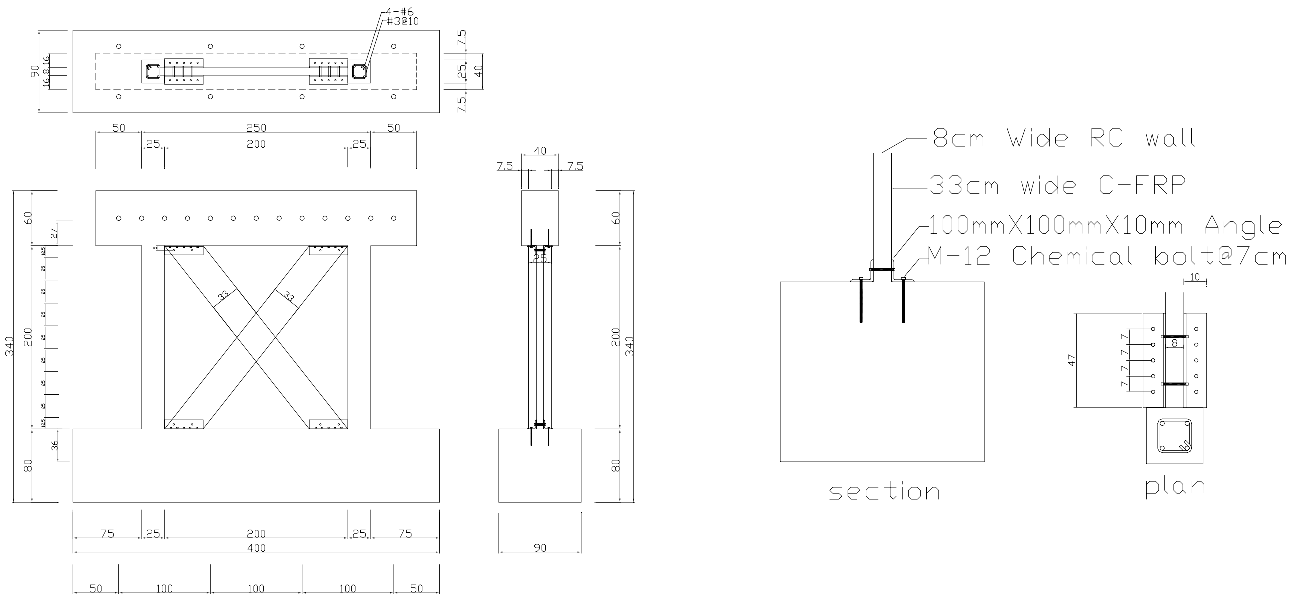
Table 1 The test configuration of specimens

No.	Specimen		Wall			Column section	Column rebar	Vertical rebar		Horizontal rebar	
	Height	Width	Height	Width	Thinks			Wall	ρ_v	Wall	ρ_h
MW1	340	400	200	200	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036
MW1C	340	400	200	200	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036
MW1C2	340	500	200	300	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036
LW1	340	500	200	300	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036
LW1R	340	500	200	300	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036
LW1C	340	500	200	300	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036
LW1Ca	340	500	200	300	8	25×25	4-D16	#3@25	0.0036	#3@25	0.0036

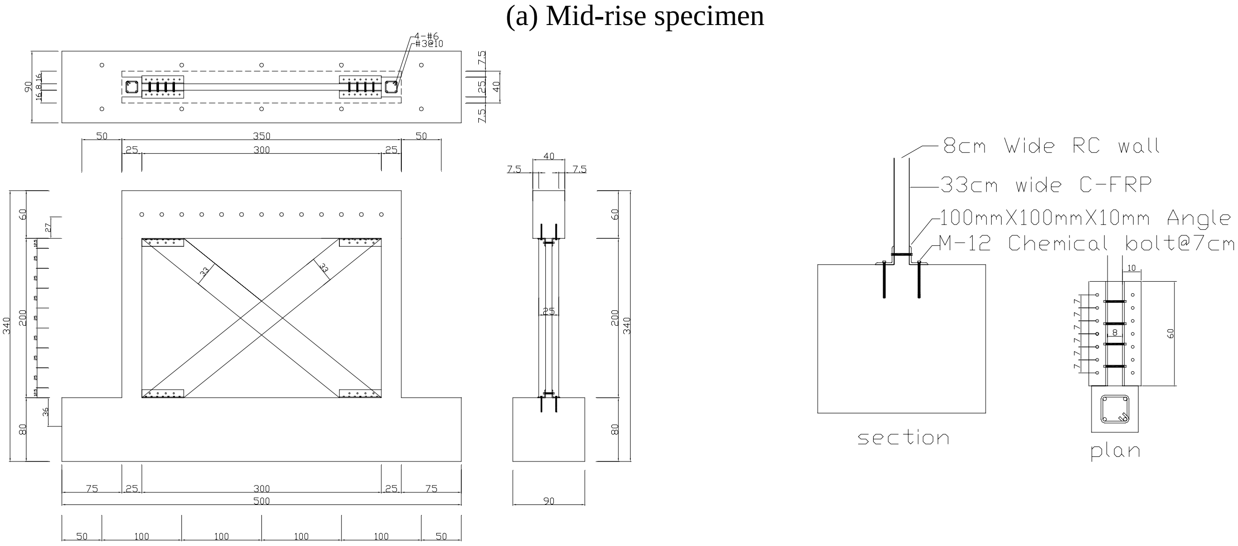
Unit: cm

Table 2 The test results of specimens

No.	f'_c (MPa)	f_y of column rebar (MPa)	f_y of wall rebar (MPa)	P_{cr} (kN)	Δ_{cr} (mm)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)	Energy dissipation (kN-mm)	Ductility factor $\left(\Delta_u/\Delta_y\right)$
MW1	28.6	515.48	364.56	253	0.11	305	0.35	493	5.66	2472.49	16.17
MW1C	28.6	515.48	364.56	180	0.17	325.8	0.75	576	5.72	2750.92	7.63
MW1C2	28.6	515.48	364.56	180	0.26	329.4	1.65	657	6.46	3065.88	3.91
LW1	27.3	515.48	364.56	180	0.1	287.79	0.65	660.02	7.99	3273.16	12.29
LW1R	27.3	515.48	364.56					440	5.0	1335.24	
LW1C	27.3	515.48	364.56	319	0.5	452.13	1.26	867	4.37	4281.33	3.47
LW1Ca	24.3	526.34	372.43	326	0.9	384.95	1.21	653	13.79	7931.8	11.4

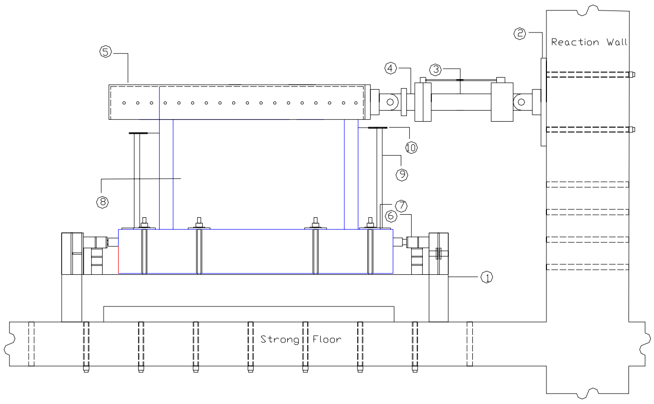


(a) Mid-rise specimen

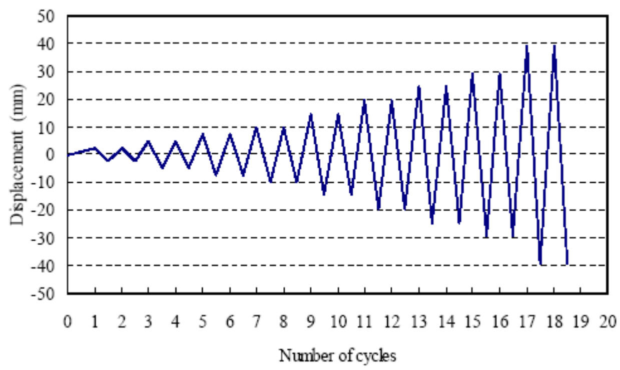


(b) Low-rise specimen

Figure 1 Schematic configuration of representative specimen

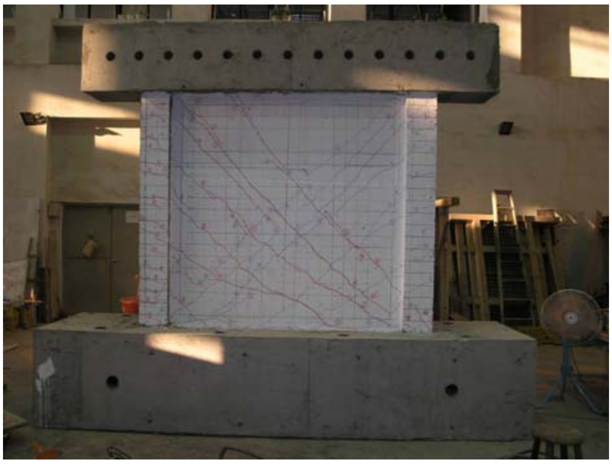


(a) Experimental system

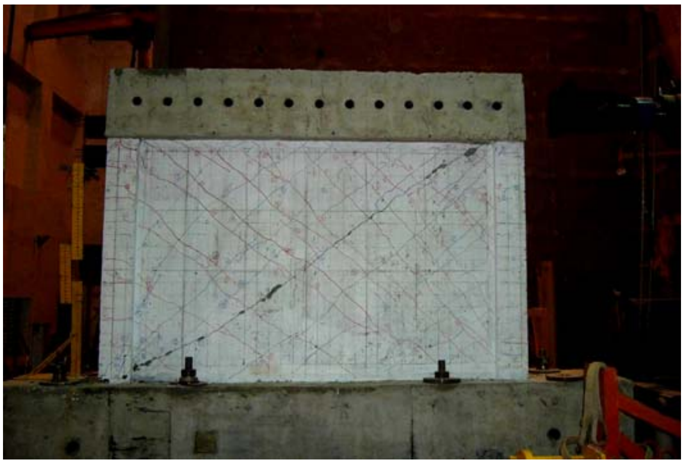


(b) Loading history

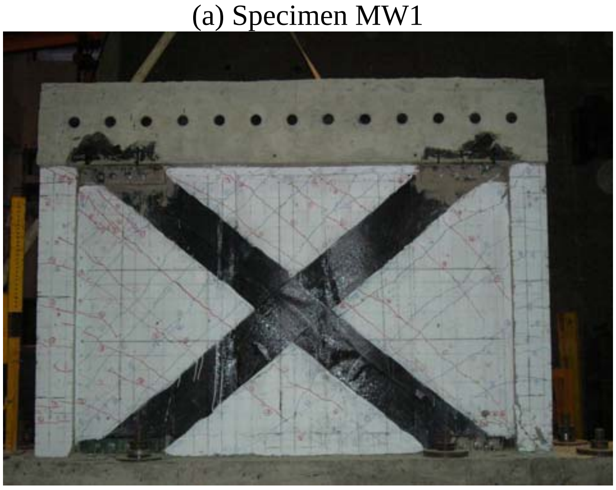
Figure 2 Experimental configuration



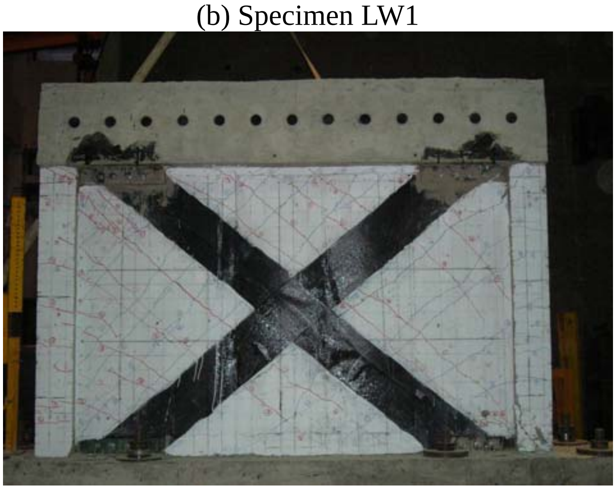
(a) Specimen MW1



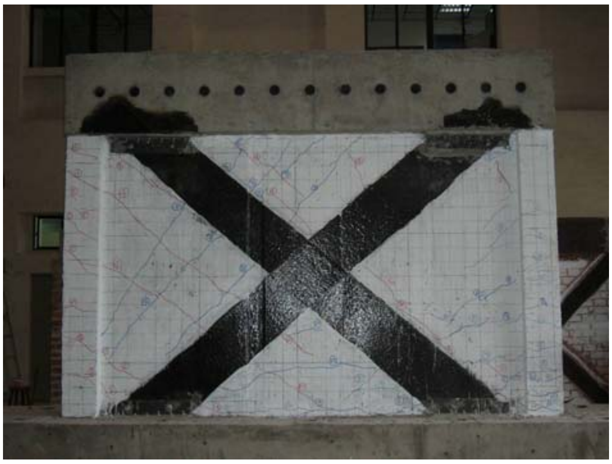
(b) Specimen LW1



(c) Specimen LW1R



(d) Specimen LW1C

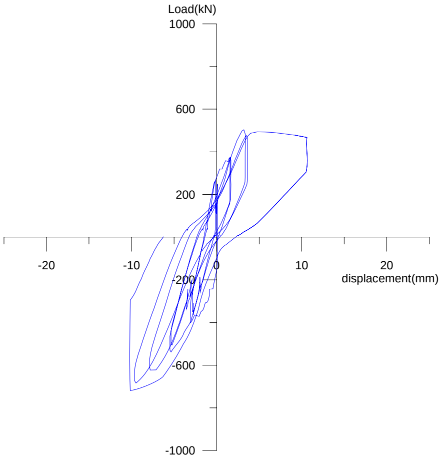


(e) Specimen LW1Ca

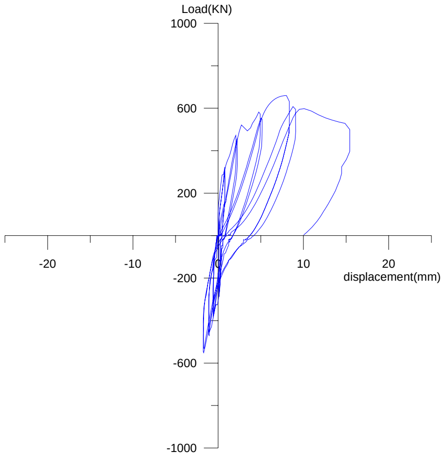
(f) Specimen MW1C

(g) Specimen MW1C2

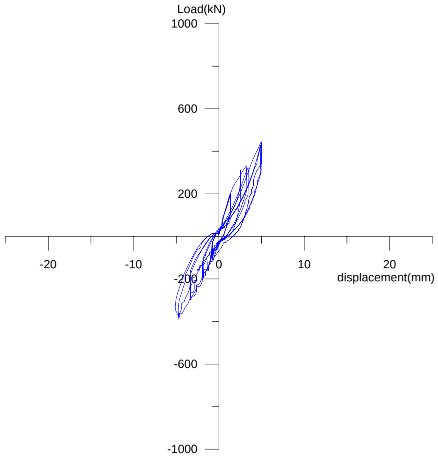
Figure 3 Pictures of tested specimens



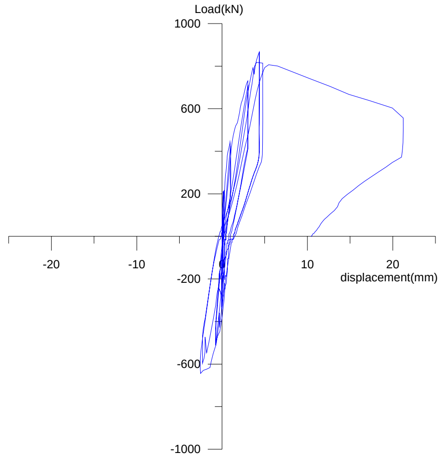
(a) Specimen MW1



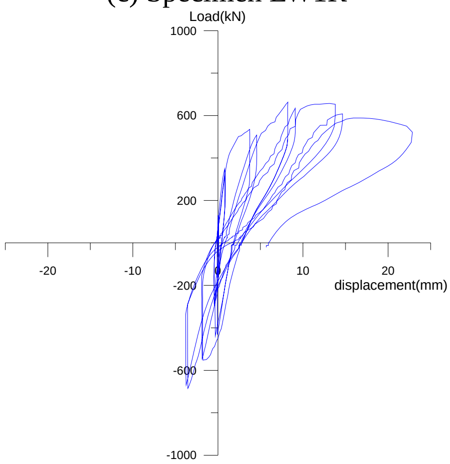
(b) Specimen LW1



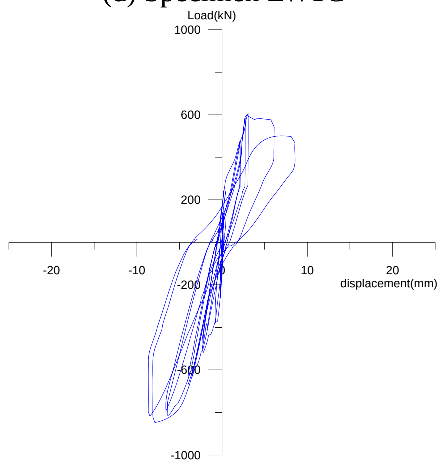
(c) Specimen LW1R



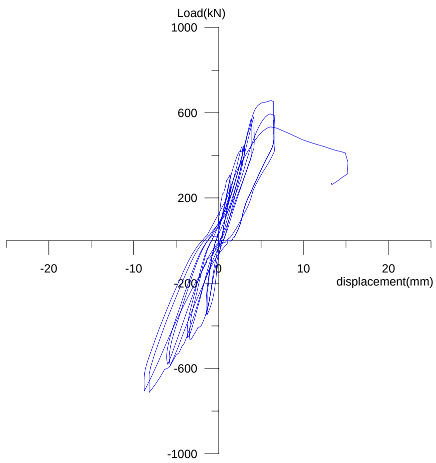
(d) Specimen LW1C



(e) Specimen LW1Ca



(f) Specimen MW1C



(g) Specimen MW1C2

Figure 4 Load-displacement curves of specimens