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FLEXURAL BEHAVIOR OF RM CONCRETE BLOCK WALL GIRDERS

by

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INTRODUCTION

Seismic tests of RM concrete block wall girders have been carried out under cyclic bending and shear loading condition since 1985. Four wall girders were tested in 1985 with the test parameters of the amounts of shear reinforcement and shear span ratios (Ref. 1), other four wall girders were tested in 1986 with the test parameters of lap splices of flexural reinforcing bars at the wall girder ends and spiral reinforcement to confine the grouted concrete around the splices (Refs. 2 and 3), and the rest four were tested in 1988 with the test parameters of diameters of flexural reinforcing bars and the details of bar arrangement (Ref. 4). The main purpose of the tests was to provide data for the development of a new masonry structural system without reinforced concrete beams required strongly in the existing Masonry Building Codes in Japan.

The objective of this paper is to describe strength, ductility and failure mechanism of reinforced concrete block wall girders with spirally-reinforced lap splices obtained by cyclic bending and shear tests. The main purpose of the tests was to provide data for the development of a new masonry structural system without reinforced concrete girders required strongly in the existing Building Codes in Japan. In this paper, the influences of lap splices of reinforcing bars at the ends of wall girders and spiral reinforcement around the splices are described.

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OUTLINE OF WALL GIRDERS

Amounts of reinforcement and bar arrangement of four wall girders are shown in Table 1. The test parameters of the wall girders named as GF4, GF4S, GF4L and GF4SL are the details of bar arrangement (i.e., presence of lap splices of flexural reinforcing bars and/or spiral reinforcement). The wall girders were designated such that the forth and fifth letters indicate the type of parameters (i.e., a letter S indicates spiral reinforcement and a letter L indicates lap splices). Table 2 shows material properties of reinforcing bars, and Table 3 shows results of compression tests of joint mortar, RM assemblage; prism test, and grout concrete. The dimensions of test wall girders are shown in Fig. 1. Depth, width and clear span length, which are common to all wall girders, are 790 mm, 190 mm and 2,000 mm long, respectively, and the shear-span-to-depth ratio is 1.27. The wall girders, which consisted of four layers of concrete RM units, were grouted in its position of the real practice in Japan. The nominal diameter of flexural reinforcing bars is 19 mm; #6, and the flexural and shear reinforcement ratios are 0.75 and 0.34 in percent, respectively.

In the cases of wall girders; GF4L and GF4SL, the length of lap splices of flexural reinforcing bars at the wall girder ends is 760 mm equal to forty times nominal diameter of flexural reinforcing bars which is the minimum length required in the draft Seismic Design Guidelines. As were the cases for wall girders GF4S and GF4SL, spiral reinforcement is 790 mm in length, which is the same value as the depth of the wall girders.

TEST METHOD

All wall girders were loaded to cause inverse symmetric bending moment distributions by the equipment shown in Fig. 2. The reinforced concrete end stubs were fixed to the test floor and an L-shaped loading beam, respectively. Cyclic loading was applied by the following schedule in principle: 1 cycle at the average deflection angle of the both ends of the wall girder of $\pm$1/2000 rad., 2 cycles at $\pm$1/400 rad., $\pm$1/200 rad., $\pm$1/100 rad., respectively, 1 cycle at $\pm$1/50 rad., and a monotonic loading until severe strength deterioration occurs. Relative displacement between the both ends, shear deformation, slip and elongation of flexural reinforcement from the end stubs, and strains of flexural, shear and spiral reinforcing bars were measured as shown Figs. 3 and 4, respectively.

TEST RESULTS

As was the case for a wall girder GF4SL, during the second loop of the scheduled deflection angle of both ends of +1/200 rad., deflection over +1/100 rad. was applied due to a trouble of the loading system. However, the deformation behavior of the wall girder under the trouble was not recorded. The schedule of cyclic loading was, therefore, slightly changed for this wall girder.

Initial Stiffness

Initial stiffness of all wall girders was estimated by the A.I.J. formula for reinforced concrete structures, where the strengths; Fm obtained by prism tests were used for compressive strengths of concrete; Fc. Initial stiffness was calculated by the beam theory considering both flexural and shear deformation as follows;

$$K = 1 \Big/ \left\{ \frac{\ell^3}{12 \cdot Em \cdot I} + \frac{\kappa \cdot \ell}{Gm \cdot A} \right\} \quad \text{(tonf/cm)} \qquad (1)$$

where, ℓ : clear span length (cm)

Em : Young's modulus of RM assemblage (kgf/cm^2)

$Em = 1.68 \times 10^5 \sqrt{Fm/180}$

Fm : prism strength (kgf/cm^2)

I : geometrical moment of inertia (cm^4)

κ : section ratio (=1.2)

Gm : shear modulus (kgf/cm^2)

$Gm = \frac{Em}{2(1+\nu m)}$ (kgf/cm^2)

νm : Poison's ratio of RM assemblage (=1/6)

A : section area (cm^2)

Secant stiffness of shear force-deflection relationships at the stage, in which nominal shear stress was 3.0 kgf/cm^2, was used for estimating initial stiffness by the tests. The experimental and calculated values are shown in Table 4. The experimental values are 0.43-0.69 times of the calculated values.

Crack Patterns

Crack patterns at the average deflection angle of the both ends of 1/50-1/63 rad. are shown in Fig. 5. Initial flexural cracks were observed along vertical mortar joints at the ends, when the average shear stresses were 3.1-5.3 kgf/cm^2, and shear cracks also occurred, when the average shear stresses were 8.4-12.9 kgf/cm^2 as shown in Table 5. Yield in bending was observed, when the average shear stresses were 9.6-12.7 kgf/cm^2, and the average stresses at the ultimate stages were 11.4-13.7 kgf/cm^2 as shown in Table 6.

Shear cracks were remarkably developed after yield, and in the cases of wall girders GF4 and GF4S without lap splices, combined bending and shear failure occurred finally by increase of these cracks. The failure characteristics of these wall girders had not any significant difference except that occurrence of bond splitting failure seemed to be delayed by spiral reinforcement. In the cases of wall girders GF4L and GF4SL with lap splices, the wall girders failed with increase of the initial cracks because of slipping of flexural reinforcing bars on lap splices. As was the case for the wall girder GF4L finally failed in bond splitting.

Observed Strengths

Strengths and deflection angles at flexural and shear cracking stages are shown in Table 5. Those at yield and ultimate stages are shown in Table 6. The strengths are expressed as average shear stresses. The flexural and shear cracking strengths, shear forces at flexural yield and shear strengths were calculated using the following A.I.J. (Architectural Institute of Japan) formulas (2)-(5), for reinforced concrete beam, respectively.

Flexural Cracking Strength:

$$Q_{Mc} = 1.8\sqrt{Fm}\cdot Z\cdot 2/\ell \quad \text{(tonf)} \qquad (2)$$

where, Fm : prism strength (kgf/cm^2)
Z : section modulus (cm^3)

Shear Cracking Strength:

$$Q_{Sc} = \frac{0.085\cdot kc(500+Fm)}{M/(Q\cdot d)+1.7} A \quad \text{(tonf)} \qquad (3)$$

where, kc : section ratio (=0.72)

$M/(Q\cdot d)$: shear span ratio ($1 \leq M/(Q\cdot d) \leq 3$)

M : maximum bending moment

Q : shear force

d : effective depth of wall girder

Shear Force at Yield:

$$Q_{Mu} = 0.9\cdot At\cdot \sigma y\cdot d\cdot 2/\ell \quad \text{(tonf)} \qquad (4)$$

where, At : area of flexural reinforcing bars (cm^2)

σy : yield strength of flexural reinforcing bars (kgf/cm^2)

d : effective depth of wall girder (cm)

Shear Strength:

$$Q_{Su} = \left\{ \frac{0.053\cdot pt^{0.23}(180+Fm)}{M/(Q\cdot d)+0.12} + 2.7\sqrt{pw\cdot \sigma wy} \right\} b\cdot j \quad \text{(tonf)} \qquad (5)$$

where, pt : flexural reinforcement ratio (%)

pw : shear reinforcement ratio

σwy : yield strength of shear reinforcing bars (kgf/cm^2)

b : width of wall girder (cm)

j : distance between centroids of tensile and compressive forces in section (cm) ($=7/8\cdot d$)

Observed maximum strengths are 1.29-1.55 times as large as the calculated flexural strength, and 0.67-0.81 times of the shear strengths. From comparison of calculated values and observed values during tests, it is concluded that all wall girders took yield by bending.

Overall Behavior of Load-Deformation Characteristics

Since the discrepancy between the deflections measured at the both ends was observed in large deformation range due to the rotation of the loading beam, each relationship at each end is shown in Fig. 6. Behavior of the restoring force characteristics was almost equivalent to those of reinforced concrete beams, and had a large energy absorption within the deflection angle of about 1/100 rad..

Ratio of Flexural Deformation to Total Deformation

Flexural deformation to total deformation relationships are shown in Fig. 7. Broken lines in the figure show the relationships of flexural deformation to total deformation based on reinforced concrete beam elastic theory. As were the cases for wall girders GF4S and GF4SL in '86 test series, the shares were larger than the theoretical values, however the discrepancies were not remarkable. In the case of a wall girder GF4, after the average deflection angle was 1/200 rad., the contribution of flexural deformation to total deformation decreased according to the increase of total deformation. The contribution was almost constant at the average deflection angle of over 1/200 rad. in the cases of wall girders GF4S and GF4L, at the average deflection angle of over 1/150 rad. in the case of a wall girder; GF4SL. The decrease of the contribution in the cases of wall girders GF4L and GF4SL with lap splices were small because the flexural deformation was significantly affected by the slippage of lap splices at the ends of the wall girders.

Deformation Capacity

Deformation capacity are shown in Table 7. Maximum deflection angles at strength deteriorated to 80% of maximum strength are defined as deformation capacity. When maximum deflections at both ends are different, the larger value is used. The estimated values in Table 7 correspond to deflection angles at the marks v in Fig. 7. Deformation capacity of all wall girders were over 1/100 rad. in terms of deflection angle. Spiral reinforcement is effective to improve deformation capacity. The maximum deformation corresponding to deformation capacity in the case of a wall girder; GF4SL was not recorded due to the trouble of the loading system. Hence, the deformation capacity shown in Table 7 may be underestimated.

CONCLUDING REMARKS

Strengths and deformation capacity of RM concrete block wall girders yielded in bending were similar to those of reinforced concrete beams. The strengths could be estimated by reinforced concrete theory. Deformation capacity in terms of deflection angle is concluded over 1/100 rad.. Effects of spiral reinforcement are not remarkable in the case of a wall girder without lap splices of flexural reinforcing bars at the ends. In the case of using the lap splices, it is effective to use spiral reinforcement to avoid bond splitting failure and to improve the ductility.

ACKNOWLEDGMENTS

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Table 1 : Properties of test wall girders (unit : mm)

Specimen	Clear Span	Flexural Reinforcement Amount	Spiral	Splice	Shear Reinforcement	Test Series
GF4	2,000 [1.27]	2−D19 (0.42%)	×	×	1−D13 @200 (0.34%)	'85
GF4S				○		'86
GF4L			○	×		'88
GF4SL				○		'86

Note : A value in brackets is a shear-span-to-depth ratio.
Values in parentheses are reinforcement ratios.

Table 2 : Material Properties of Reinforcing Bars

	D13	D16	D19
Yield Strength (kg/cm²)	3,702 3,656 3,619	3,676 3,550 3,672	3,630 3,621 3,695
Tensile Strength (kg/cm²)	5,415 5,433 5,346	5,371 5,308 7,152	5,404 5,620 5,369
Tensile Strain (%)	23.6 23.1 18.7	25.0 26.5 23.1	23.7 24.3 22.8

Note : Upper Values : Test Series '85
Middle Values : Test Series '86
Lower Values : Test Series '88

Table 3 : Results of Compression Tests (kgf/cm^2)

Specimen	Joint Mortar	Grout Concrete	RM Assemblage
GF4	149.4	358.6	216.9
GF4S	221.0	229.4	257.1
GF4L	453.4	319.8	282.7
GF4SL	275.9	299.4	257.1

Table 4 : Initial Stiffness (tonf/cm)

Specimen	Exp. Value	Cal. Value	Ratio of Exp/Cal
GF4	103.2	150.3	0.69
GF4S	92.6	163.6	0.57
GF4L	87.5	171.6	0.51
GF4SL	70.7	163.6	0.43

Table 5 : Cracking Strength (kgf/cm²)

Specimen	Flexural Crack			Shear Crack		
	$_t\tau_{mc}$	Exp/Cal	$_tR_{mc}$	$_t\tau_{sc}$	Exp/Cal	$_tR_{sc}$
GF4	3.98	1.14	0.31	10.37	0.94	2.49
	4.64	1.33	0.36	9.59	0.87	2.17
GF4S	3.31	0.87	0.28	12.90	1.11	4.68
	3.35	0.88	0.12	9.99	0.86	1.94
GF4L	5.16	1.29	0.46	8.39	0.70	1.56
	3.11	0.78	0.20	10.93	0.91	1.53
GF4SL	3.34	0.88	0.38	12.07	1.03	3.72
	5.30	1.40	0.26	11.78	1.01	2.23

Note : τ : Average Shear Stress (kgf/cm²), R : Deflection Angle ($\times 10^{-3}$ rad.)
Upper values are observed in positive loading, lower values are in negative.

Table 6 : Yield and Ultimate Strength (kgf/cm²)

Specimen	Yield			Ultimate			
	$_t\tau_y$	Exp/Cal	$_tR_y$	$_t\tau_u$	Exp/Cal1	Exp/Cal2	$_tR_u$
GF4	10.65	1.20	2.89	12.21	1.38	0.76	19.98
	9.61	1.08	1.89	11.43	1.29	0.71	10.69
GF4S	9.81	1.11	2.67	12.90	1.46	0.76	4.68
	12.14	1.37	3.33	13.68	1.55	0.81	9.81
GF4L	10.58	1.17	2.69	11.67	1.29	0.67	7.96
	12.62	1.40	3.01	13.27	1.47	0.76	4.07
GF4SL	12.07	1.36	3.72	12.44*	1.41	0.73	5.22*
	12.68	1.43	2.45	13.66	1.54	0.81	9.84

Note : τ : Average Shear Stress (kgf/cm²), R : Deflection Angle ($\times 10^{-3}$ rad.)
Cal1 : Calculated shear force at yield, Cal2 : Calculated shear strength
Upper values are observed in positive loading, lower values are in negative.
Values with a mark * are underestimated.

Table 7 : Deformation Capacity in Deflection Angle ($\times 10^{-2}$ rad.)

Specimen	Observed Value				Deformation Capacity		
	Left		Right		+	−	Average
	+	−	+	−			
GF4	1.50	1.41	2.03	1.08	2.03	1.41	1.72 (1/58)
GF4S	0.687	2.33	1.13	3.52	1.13	3.52	2.33 (1/43)
GF4L	0.638	0.960	1.10	0.823	1.10	0.960	1.03 (1/97)
GF4SL	0.48*	1.15	1.05*	1.39	1.05*	1.39	1.22*(1/82)

Note : Values in ░░░ are the larger in each loading direction.
Values with a mark * are underestimated.

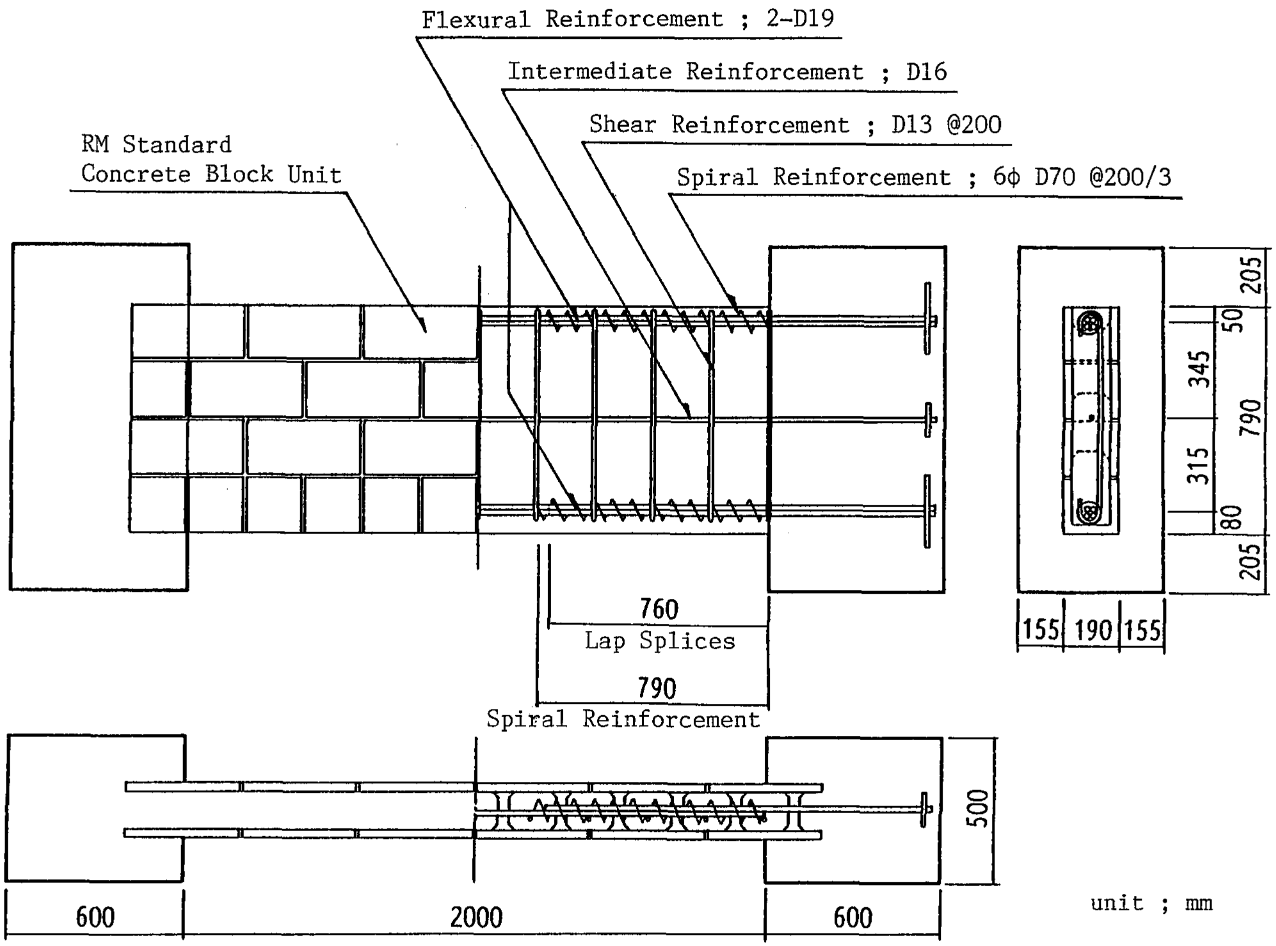


Fig. 1-1 Dimensions of Wall Girder (GF4SL)

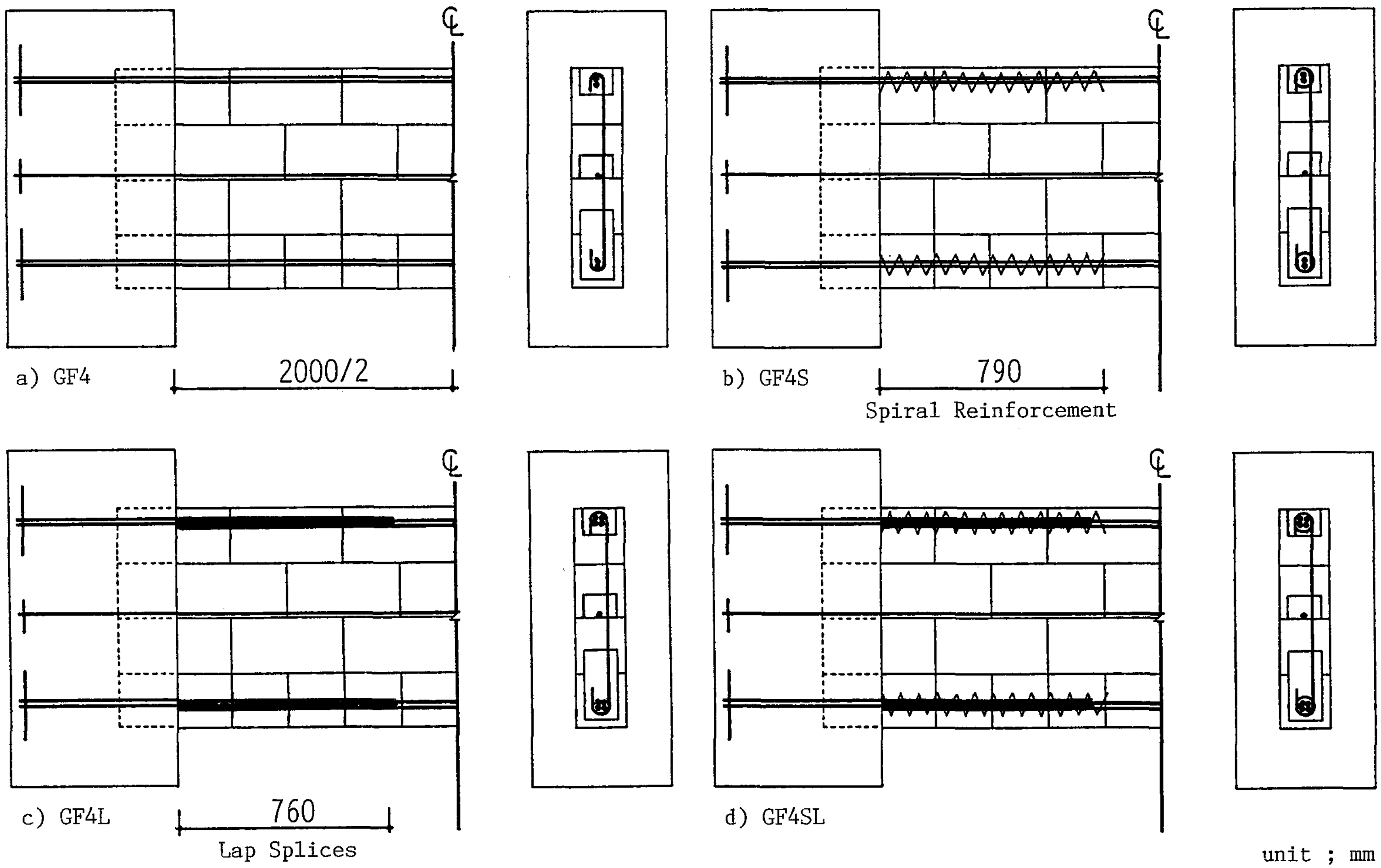


Fig. 1-2 Dimensions of Wall Girders

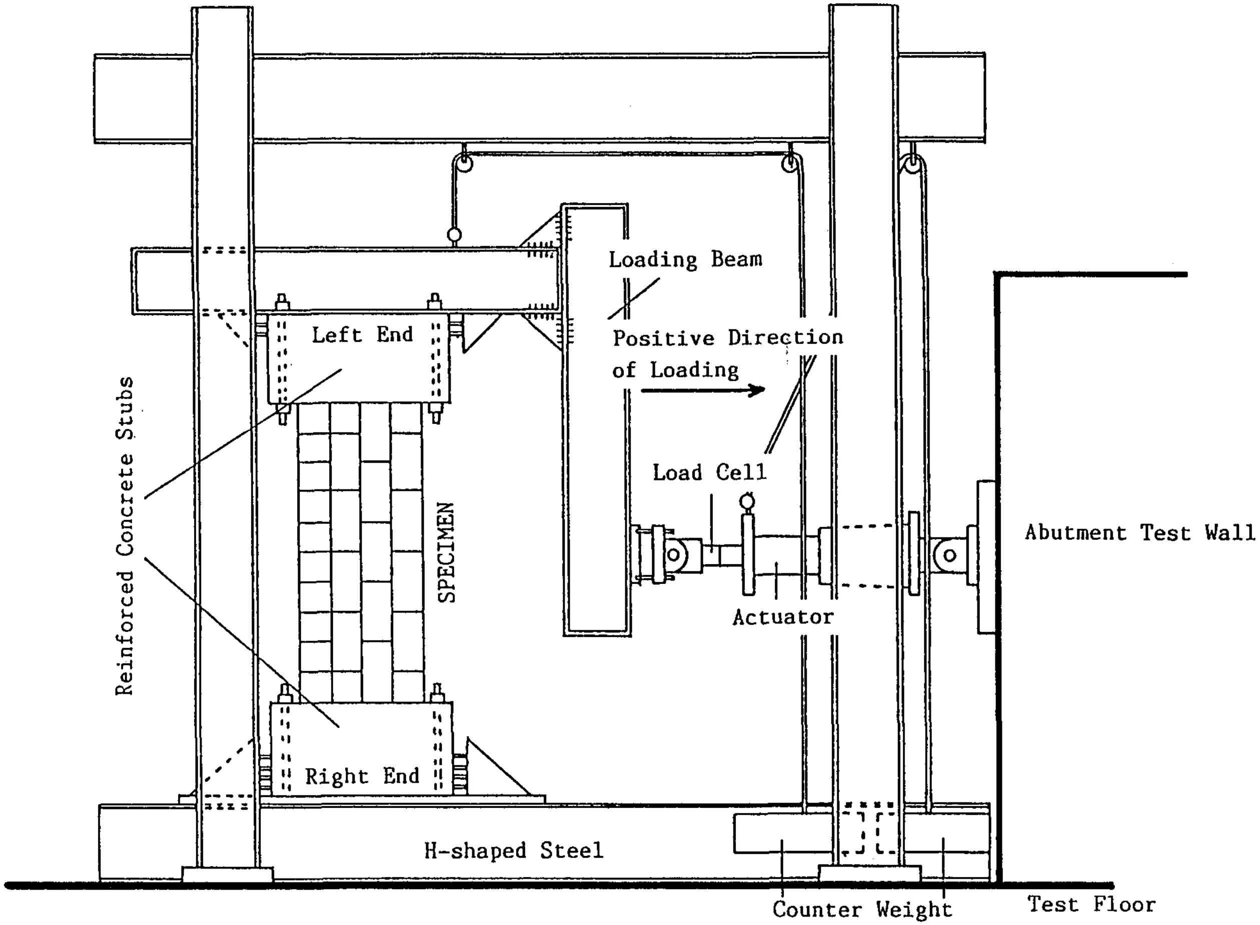


Fig. 2 Loading System

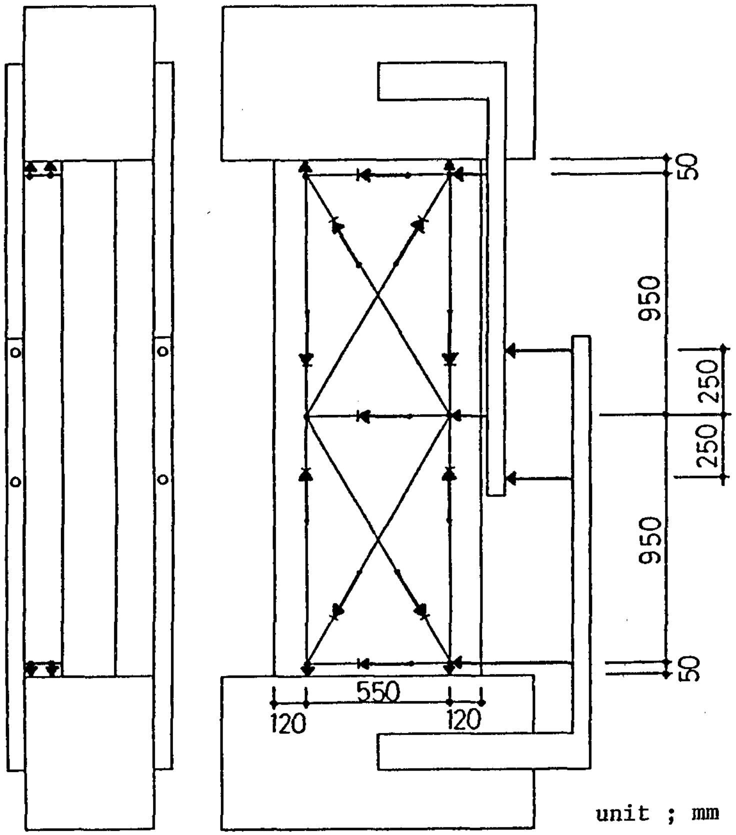


Fig. 3 Locations of Displacement Transducers

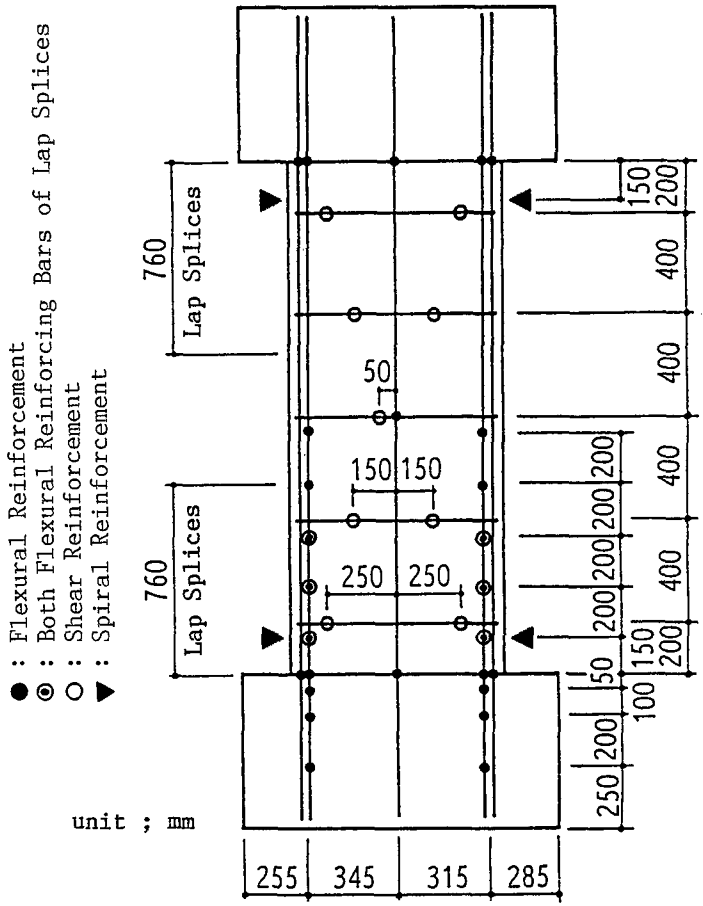


Fig. 4 Locations of Strain Gages

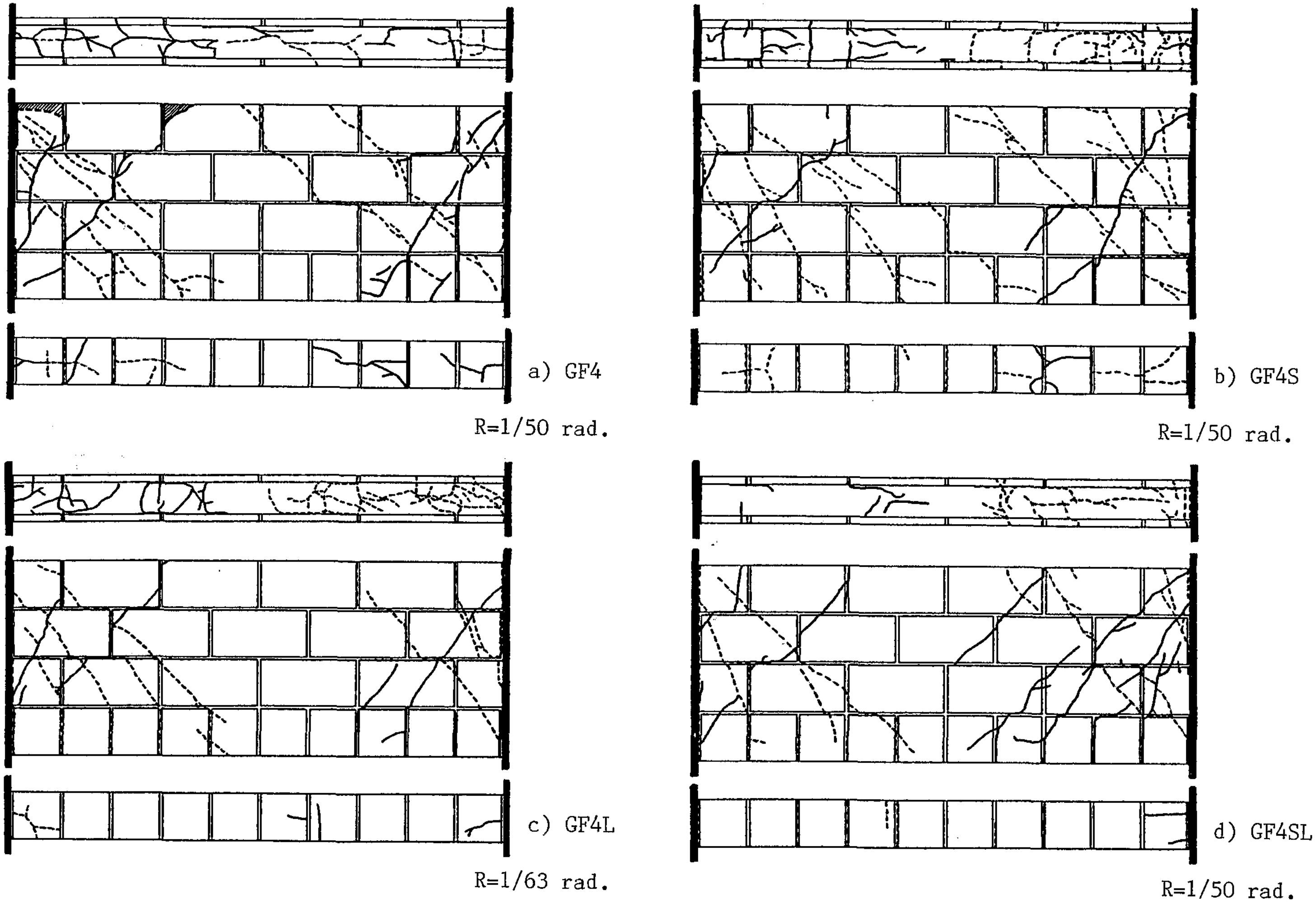


Fig. 5 Crack Patterns

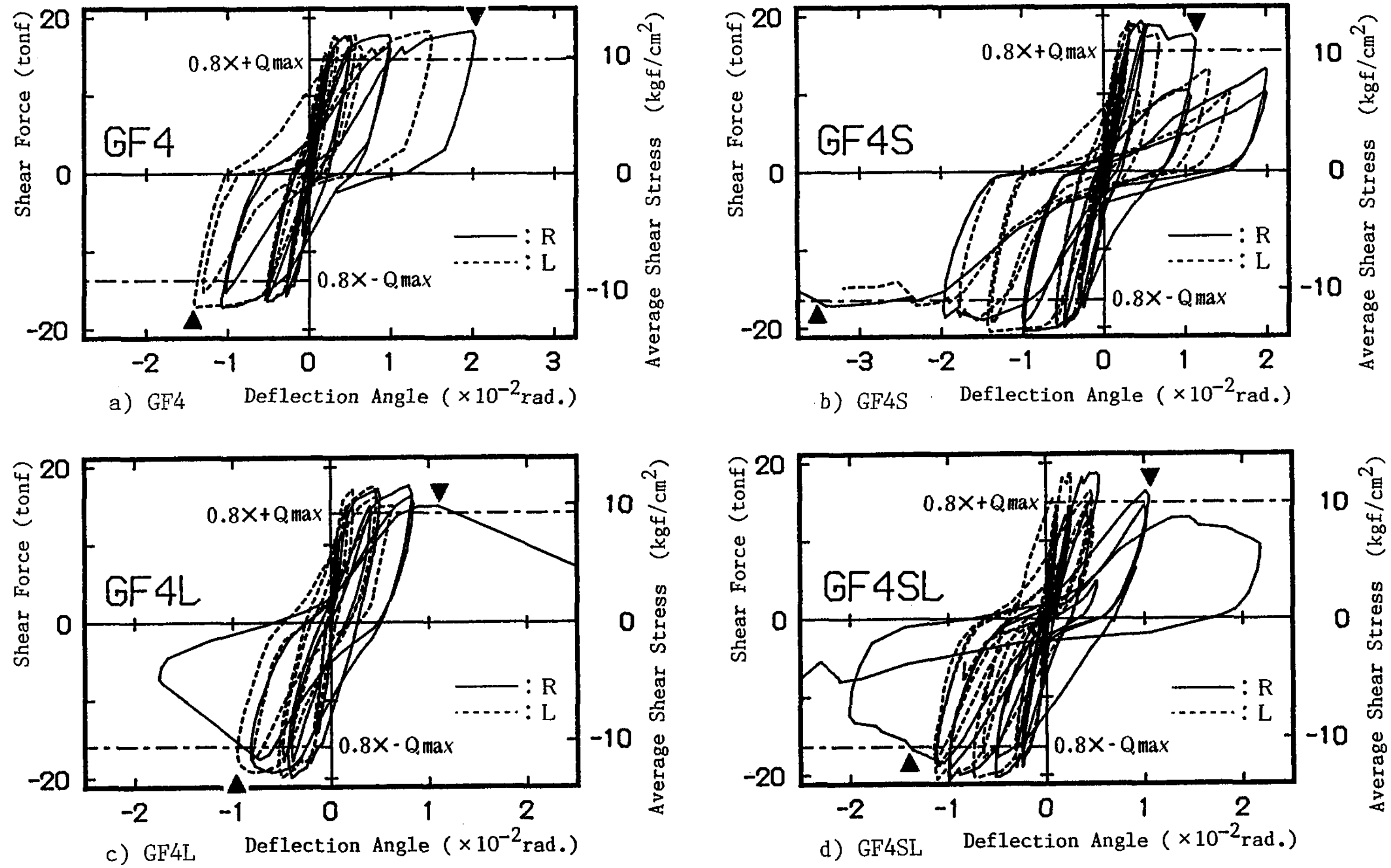
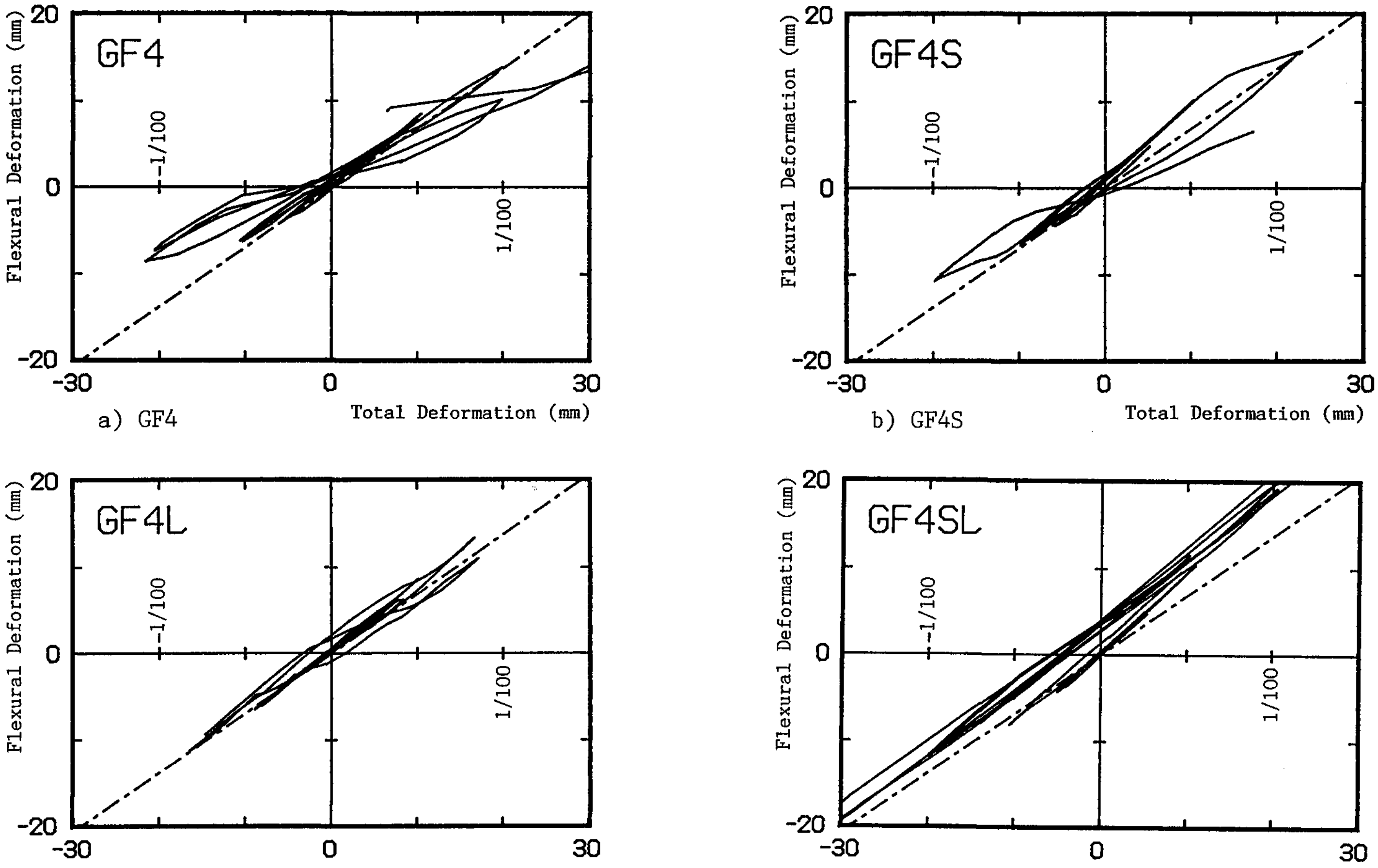


Fig. 6 Shear Force-Deflection Angle Relationships



a) GF4 b) GF4S c) GF4L d) GF4SL

Fig. 7 Flexural Deformation-Total Deformation Relationships