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FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BLOCK MASONRY BEAMS WITH SPIRALLY-REINFORCED LAP SPLICES

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SUMMARY

Research on reinforced masonry structure has been carried out as the third phase of U.S.-Japan Coordinated Earthquake Research Program since 1984 (Refs. 1-3). Reinforced concrete block masonry beams were tested under cyclic bending and shear loading condition to cause an inverse symmetric moment distribution for simulating earthquake condition. The test parameters were the amount of shear reinforcement, shear span ratio, lap splice of tensile reinforcement at the end of beam and spiral reinforcement around the splices. Their influence to strength, ductility and failure mechanism were examined.

INTRODUCTION

The objective of this paper is to describe strength, ductility and failure mechanism of reinforced concrete block beams obtained by cyclic bending and shear tests. The main purpose of the test was to provide data for the development of a new masonry structural system without reinforced concrete beams required strongly in the existing Building Codes in Japan. In this paper, influence of the amount of shear reinforcement, shear span ratio, lap splice of tensile reinforcement bars at the ends of beam and spiral reinforcement around the splices obtained through the test series is described.

TEST BEAMS AND METHOD OF TESTING

The number of specimens is seven. Four beams; GF3, GF4, GF5D and GF6, were tested to investigate the flexural behavior of reinforced concrete block beams. The test parameters were shear reinforcement and shear span. Two beams with lap splices and spiral reinforcement; GF4SL and GF5SL, were also tested. Besides them, a beam with spiral reinforcement but without lap splice; GF4S, was tested to investigate the effectiveness of spiral reinforcement. The beams are designated such that the forth and fifth letters indicate the type of parameter;i.e., S indicates spiral reinforcement and L indicates lap splices. The dimension of specimen with lap splices and spiral reinforcement and detail of lap splices and spiral reinforcement are shown in Fig. 1. Amounts of reinforcing bars, shear span ratios, lap splices and spiral reinforcement are shown in Table 1.

Mechanical characteristics of the materials used for the test specimens are shown in Tables 2 and 3. Loading system is shown in Fig. 2. Relative displacement between both ends, shear deformation, slip and elongation of reinforcing bars from the end stubs, and strains of reinforcing bars were measured as shown in Fig. 3. Cyclic loading were applied by the following schedule in principle: 1 cycle at the deflection angle between both ends of ±1/2000, 2 cycles at ±1/400, ±1/200, ±1/100 and ±1/50, and a monotonic loading until the severe strength deterioration occurs.

TEST RESULTS

Overall Behavior of Load-Deformation Characteristics Shear stress vs. joint translation angle relationships are shown in Fig. 4. The envelops of relative deflection angle measured at the both ends are separately shown in Fig. 5, since the discrepancy between the relative deflection angles measured at the both ends was observed in large deformation range due to the rotation of loading beam. The marks ▼ in Fig. 5 show deflection capacity of each end of beam. As was the case for beam GF4SL, during the second loop of the scheduled deflection angle of both ends of +1/200, the deflection over +1/100 was applied due to the trouble of loading system. Therefore, the schedule of cyclic loading was slightly modified for the beam. Behaviors of the restoring force characteristics were almost equivalent to those of reinforced concrete beams, and had a large energy absorption within the deflection angle of about 1/100 except the short span beam GF6. Energy absorption of GF5D and GF5SL having heavy web reinforcement were larger than GF3, GF4, GF4S or GF4SL.

The crack patterns at the scheduled deflection angle of 1/50 are shown in Fig. 6. The initial flexural cracks were observed along vertical mortar joints at the ends of beams, when the average shear stress ($\bar{\tau}$) was 3.3-4.0 kg/cm^2 except GF6. After flexural shear cracks occurred, yielding in bending was observed when $\bar{\tau}$ was 10-12 kg/cm^2. Shear cracks were developed after yielding in the cases of GF3, GF4 and GF4S without lap splices, and the combined bending and shear failure finally occurred. However, in the cases of GF4SL and GF5SL with lap splices and spiral reinforcement, the beams failed with increasing of initial flexural cracks along vertical mortar joints at the end of beams because of the slipping of reinforcing bars on lap splices. Shear cracks were not developed. The beam GF5D failed with increasing of flexural shear crack because of large shear strength. Compared the beam GF4 with the beam GF4S, the spiral reinforcement seemed to delay bond splitting failure. As was the case for short beam GF6, initial flexural cracks and shear cracks were observed when $\bar{\tau}$ was 6.6 and 16.1 kg/cm^2, respectively. It also yielded in bending first, however failed in shear finally with diagonal crack when $\bar{\tau}$ was about 19 kg/cm^2.

Ratio of Flexural Deformation to Total Deformation Flexural deformation-to-total deformation are shown in Fig. 7. Broken lines of the figure showed relationships of flexural deformation-to-total deformation based on elastic beam theory. Total deformation is calculated based on the average of relative deflection angles of both ends. As was the case for beams GF3 and GF4 without lap splice, after deflection angle was over 1/200, the flexural deformation decreased according to increase of total deformation. In the case of the beams GF4SL and GF5SL with spirally-reinforced lap splices, the share of the flexural deformation to the total deformation was almost constant because of slipping of tensile reinforcement on lap splices. In the case of GF5 series, the similar tendency was observed.

Initial Stiffness The equivalent Young's modulus of concrete block was estimated by the A.I.J. formula for reinforced concrete structure, where the compressive strength Fm' obtained by the prism test was used for compressive strength of concrete Fc. Initial stiffness were calculated by the beam theory considering both flexural and shear deformations. The secant stiffness of shear force vs. deflection relationships at initial flexural cracks was used for estimating the initial stiffness by the test. The experimental and calculated values are shown in Table 4. The experimental values are 0.34-0.60 times of the calculated values.

Ultimate Strength Table 5 shows the strengths observed under the positive loading. Average shear stress and deflection angle at cracking stages are also shown in Table 5. The experimental and calculated ultimate strength expressed as an average shear stress are shown in Table 6. The ultimate strength was calculated using the following formulas (1) and (2) for reinforced concrete beam.

For shear strength:

$$Q_{Su} = \left\{ \frac{0.053 \cdot Pt^{0.23}(180+Fc)}{M/(Q \cdot d)+0.12} + 2.7\sqrt{Pw \cdot \sigma wy} \right\} \cdot b \cdot j \tag{1}$$

where, $M/(Q \cdot d)$: shear span ratio, σwy : strength of web reinforcement
Fc : compressive strength of concrete, b : width of beam
Pt : tensile reinforcement ratio (%), j : distance between centroids of tensile and compressive forces in section
Pw : shear reinforcement ratio,

For shear force at flexural yielding:

$$Q_{Mu} = 0.9 \cdot At \cdot \sigma y \cdot d \cdot 2/\ell \tag{2}$$

where, At : area of tensile reinforcement, σy : strength of reinforcement
d : effective depth of beam, ℓ : length of clear span

The observed maximum strength is 1.27-1.71 times as large as the calculated values of flexural strength, and 0.66-0.97 times of shear strength. Final failure mechanisms of the beams without lap splice were shear failure and the beams with lap splices seemed to fail in bending with slip at lap splices.

Deformation Capacity Deformation capacities are shown in Table 7. Maximum deflection angle before strength deterioration occurs is defined as deformation capacity. When the maximum deflections at both ends are different, the larger value is used. Deformation capacities of beams of GF4 series and GF5 series of which shear span ratios were 1.27, were over 1/100 in terms of deflection angle. Deformation capacities of beams GF3 with shear reinforcement ratio of 0.17% and GF6 with shear span ratio of 0.76 were smaller than the others.

CONCLUDING REMARKS

Strength and deformation capacity of reinforced concrete block beams yielded in bending were similar to those of reinforced concrete beams. Strength could be estimated by reinforced concrete theory. Deformation capacity of 1/100 in terms of deflection angle can be expected for seismic design if a proper amount of shear reinforcement is provided. Lap splices reinforced by spiral reinforcement did not give any significant influence to strength and ductility, but rather improved the characteristics. The cracks concentrated to the ends of the beam with lap splices due to the slip of reinforcing bars. Spiral reinforcement may delay the occurrence of bond splitting failure. Effect of spiral reinforcement to lap splice would be verified more clearly, if a beam with lap splices and without spiral reinforcement was tested.

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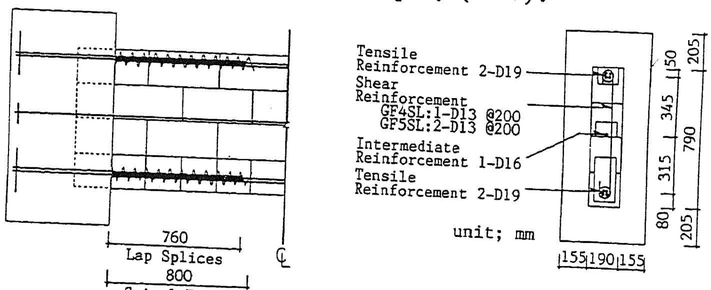

Fig. 1-1 Dimension of Specimen (GF4SL, GF5SL)

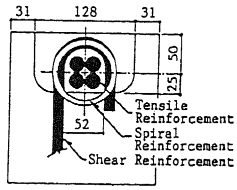

Fig. 1-2 Detail of Spiral Reinforcement and Lap Splice

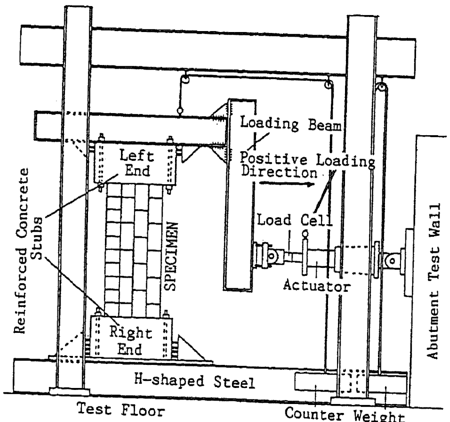

Fig. 2 Loading System

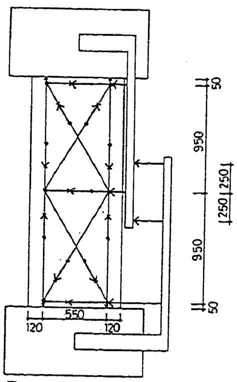

Fig. 3-1 Locations of Displacement Transducers

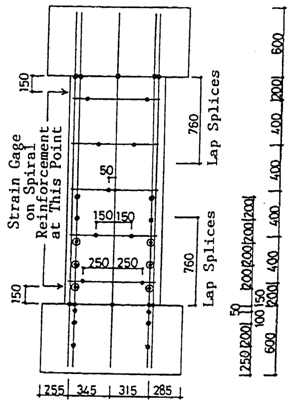

Fig. 3-2 Locations of Strain Gages

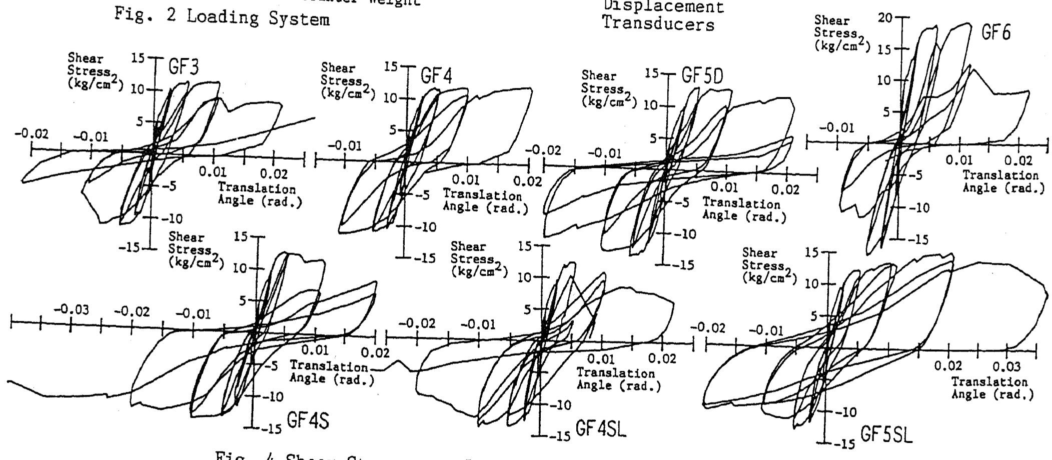

Fig. 4 Shear Stress vs. Joint Translation Angle Relationship

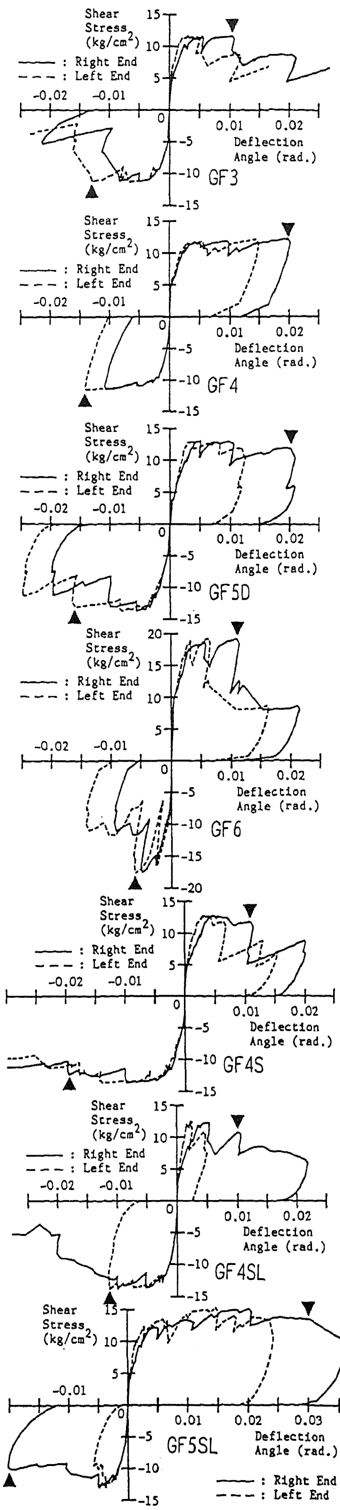

Fig. 5 Envelop of Shear Stress vs. Relative Deflection Angle Relationship

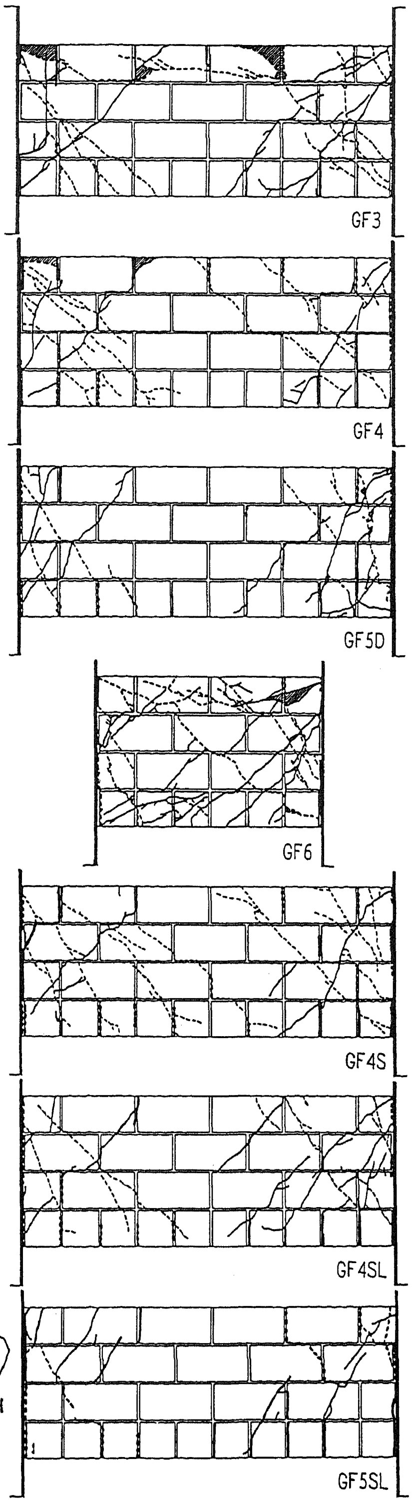

Fig. 6 Crack Patterns (Deflection Angle; 1/50 rad.)

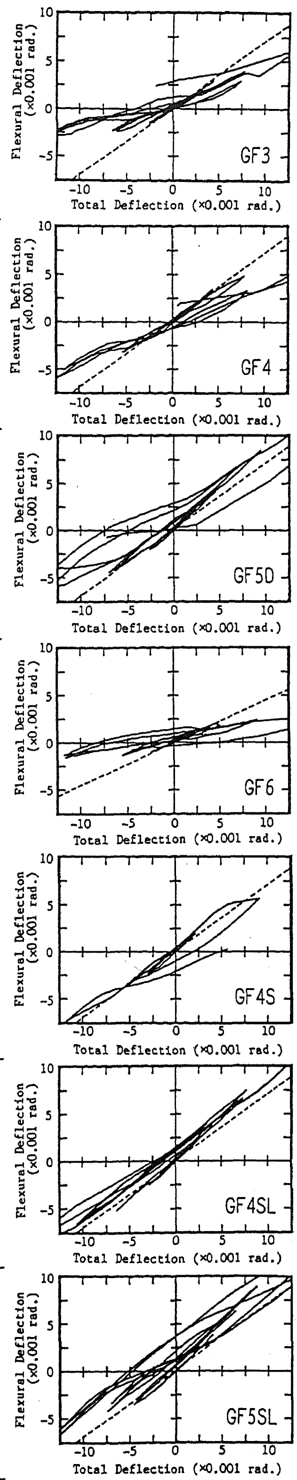

Fig. 7 Flexural Deformation vs. Average Relative Deflection Angle Relationship

Table 1 Span Length and Reinforcing Bars

Specimen	Clear Span (mm)	Tensile Reinforcement (%)	Spiral Reinforcement	Lap Splices	Shear Reinforcement (%)	Test Series
GF3	2000 1.27*	2-D19 (0.42%)	×	×	1-D13 @400 (0.17%)	'85
GF4					1-D13 @200 (0.34%)	
GF5D					2-D13 @200 (0.67%)	'86
GF6	1200 0.76*				1-D13 @400 (0.17%)	'85
GF4S	2000 1.27*		○		1-D13 @200 (0.34%)	'86
GF4SL				○		
GF5SL					2-D13 @200 (0.67%)	

Values with * are shear span ratios.

Table 2 Material properties of Reinforcing Bars (kg/cm^2)

	D13	D16	D19
Upper Yield Strength	3702 3656	3676 3550	3630 3621
Lower Yield Strength	3620 3603	3500 3483	3542 3570
Tensile Strength	5415 5433	5371 5308	5404 5620
Tensile Strain (%)	23.6 23.1	25.0 26.5	23.7 24.3

Upper values ; Test series '85
Lower values ; Test series '86

Table 5 Strength Observed during the Tests (kg/cm^2) (Positive Loading Direction)

Specimen	Flexural Crack		Shear Crack		Maximum Strength
	τc	Rc	τs	Ru	τu
GF3	3.32	0.23	10.07	4.94	11.57
GF4	3.98	0.31	10.37	2.49	12.21
GF5D	3.35	0.37	9.96	2.76	13.11
GF6	6.64	0.32	16.13	5.18	19.25
GF4S	3.31	0.28	12.90	4.68	12.90
GF4SL	3.34	0.38	12.07	3.72	12.44
GF5SL	3.99	0.44	11.56	3.43	15.26

τ : Average Shear Stress (kg/cm^2)
R : Deflection Angle (×0.001 rad.)

Table 3 Results of Compression Test (kg/cm^2)

Specimen	Joint Mortar	Grout Concrete	Prism
GF3	168.7	362.9	216.9
GF4	149.4	375.8	
GF5D	288.6	299.4	257.1
GF6	174.6	381.0	216.9
GF4S	221.0	299.4	257.1
GF4SL	275.9		
GF5SL	246.4		

Table 6 Ultimate Sterngth (kg/cm^2)

Specimen	Exp. Values τ	Cal. Values		Ratio of Exp./Cal.	
		τmu	τsu	$\tau / \tau mu$	$\tau / \tau su$
GF3	11.57	9.06	14.6	1.28	0.79
GF4	12.21		16.8	1.35	0.73
GF5D	13.73	8.91	20.8	1.54	0.66
GF6	19.25	15.10	19.9	1.27	0.97
GF4S	13.68	8.91.	17.7	1.54	0.77
GF4SL	13.66			1.53	0.77
GF5SL	15.26		20.8	1.71	0.73

Table 4 Initial Stiffness (ton/cm)

Specimen	Exp. Values	Cal. Values	Ratio of Exp./Cal.
GF3	107.6	178.2	0.60
GF4	97.4		0.55
GF5D	68.4	194.0	0.35
GF6	260.1	535.3	0.49
GF4S	90.4	194.0	0.47
GF4SL	65.9		0.34
GF5SL	67.7		0.35

Table 7 Deflection Capacities in Deflection Angle (×0.01 rad.)

Specimen	Observed Values				Estimated Values		
	Left		Right		+	−	Average
	+	−	+	−			
GF3	0.47	1.29	1.05	0.83	1.05	1.29	1.17 (1/85)
GF4	1.49	1.46	2.00	1.07	2.00	1.46	1.73 (1/58)
GF5D	1.16	1.61	2.01	1.00	2.01	1.61	1.81 (1/55)
GF6	0.64	0.59	1.12	0.48	1.12	0.59	0.86 (1/116)
GF4S	0.65	1.74	1.09	1.96	1.09	1.96	1.53 (1/65)
GF4SL	0.42	1.14	1.01	0.98	1.01	1.14	1.08 (1/93)
GF5SL	2.35	0.54	3.02	1.99	3.02	1.99	2.51 (1/40)

Values in ░ are estimated deformation capacities.