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9-2-11 EXPERIMENTAL STUDY ON SEISMIC PERFORMANCE OF REINFORCED MASONRY BEAMS

Hiroshi ISOISHI[1], Masaomi TESHIGAWARA[1],
Akio NAKAOKA[2], and Toshihiko TERADA[3]

[1] Building Research Institute, Ministry of Construction, Tsukuba, Japan
[2] Hasegawa Komuten Co. Ltd., Higashi-ku, Osaka, Japan
[3] Daiwa House Kougyo Co. Ltd., Nishi-ku, Osaka, Japan

SUMMARY

Nine reinforced masonry(RM) beams were tested. Cyclic loading was applied to the specimen under the condition that the axial compressive stress was kept to be zero and the rotation at the both ends of a specimen was restrained. The purpose of this study is to investigate experimentally how the amount of shear reinforcement, the shear-span ratio, and the reinforced concrete(R/C) slab affect the shear and flexural behavior of RM beams.

The following conclusions were obtained;

(1) As for the rectangular RM beams which were shear failure type, the specimens with large amount of shear reinforcement showed good deformation capacity even after the diagonal tension crack occurred.
(2) The shear strength of RM beams with R/C slab was 1.38 times as much as that of the rectangular RM beams.
(3) It was experimentally confirmed that RM beams with and without R/C slab will be applicable to newly proposed medium-rise RM buildings in Japan.

INTRODUCTION

In 1984, the Building Research Institute, Ministry of Construction conducted seismic test of masonry beams. This test was within the scope of the U.S.-Japan Coordinated Earthquake Research Program on Masonry. The purpose of this study is to investigate experimentally how the amount of shear reinforcement, the shear-span ratio, and the R/C slab affect the shear and flexural behavior of masonry beams.

The number of specimens tested in this study was nine. Two specimens of those were constructed of clay brick masonry units, and the others were constructed of concrete block masonry units.

SPECIMEN AND TEST SETUP

Materials The concrete block masonry unit has two-webs and two open ends and the nominal dimensions are 20cm x 20cm x 40cm. The clay brick masonry unit has the same shape as the concrete block unit, but the nominal dimensions are 10cm x 20cm x 30cm. Those masonry units are shown in Fig. 1. The material properties of the specimens and the compressive prism strength are listed in Table 1.

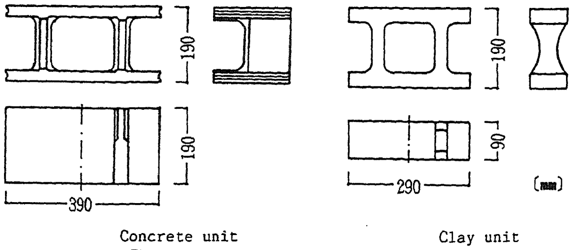

Fig. 1 Masonry Units

Table 1. Material Properties

Specimen	Prism Strength Fm' (kg/cm²)	Yielding stress, Elastic modulus (kg/cm²) (x10⁶kg/cm²)			
		Main lateral reinforcement	Shear reinforcement	Lateral reinforcement	Slab reinforcement
GF1	215.92	3500, 2.01	3620, 1.63	3289, 1.70	3554, 1.89
GF2	215.92	3542, 2.34	3620, 1.63	3289, 1.70	3554, 1.89
GF3	211.65	3542, 2.34	3620, 1.63	3289, 1.70	--
GS1	215.92	3833, 1.97	3620, 1.63	3791, 2.01	3554, 1.89
GS2	211.65	3833, 1.97	3620, 1.63	3791, 2.01	--
GS3	211.65	3833, 1.97	3620, 1.63	3791, 2.01	--
GS4	211.65	3833, 1.97	3620, 1.63	3791, 2.01	--
GSR1	274.95	3833, 1.97	3620, 1.63	3791, 2.01	--
GSR2	274.95	3833, 1.97	3791, 2.01	3791, 2.01	--

Specimens Typical beam specimens are shown in Fig. 2. The beam specimens were constructed in running bond with a 50 percent unit length overlapping in alternate beam courses, and are fully grouted by concrete.

The details of each beam are listed in Table 2. These specimens, GF1, GF2, and GS1, have R/C slab with 15cm in thickness and one meter wide on each side of the beam.

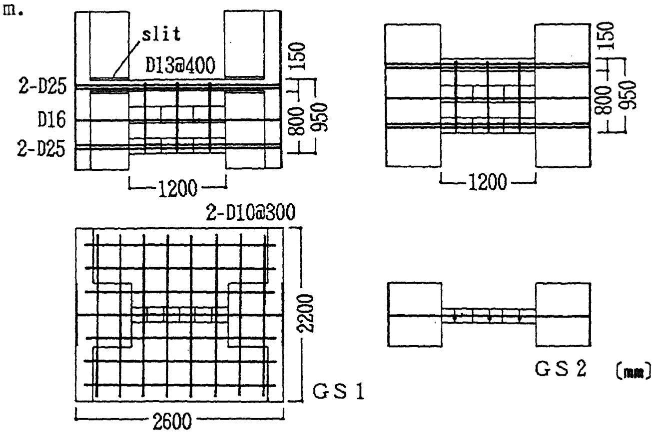

Fig. 2 Typical Beam Specimens

Table 2. Details of Specimens

Specimen	Clear span (mm)	Depth* (mm)	Width (mm)	Main lateral** reinforcement	Shear reinforcement	Slab***
GF1	1200	950	190	2-D16	D13 @200	Exist
GF2	2000	950	190	2-D19	D13 @400	Exist
GF3	2000	950	190	2-D19	D13 @400	Not Exist
GS1	1200	950	190	2-D25	D13 @400	Exist
GS2	1200	950	190	2-D25	D13 @400	Not Exist
GS3	1200	950	190	2-D25	D13 @200	Not Exist
GS4	2000	950	190	2-D25	D13 @400	Not Exist
GSR1	1200	950	190	2-D25	D13 @300	Not Exist
GSR2	1200	950	190	2-D25	D13 @150	Not Exist

* Covering Depth upper 65mm, lower 80mm   ** Lateral reinforcement D16 in all specimens   *** 2D10 @300 ℓ=2200mm, t=150mm

Test Setup The test setup(Fig. 3) employed in this study was the B.R.I. Two-Directional Test Facility(BRI/TTF). The BRI/TTF is a computer-controlled loading apparatus which can apply the in-plane force and displacement in three degrees of freedom at the top of the specimen. In this test, two vertical actuators were controlled by the computer in order to restrain the rotation of the top beam and to keep the constant vertical compressive stress.

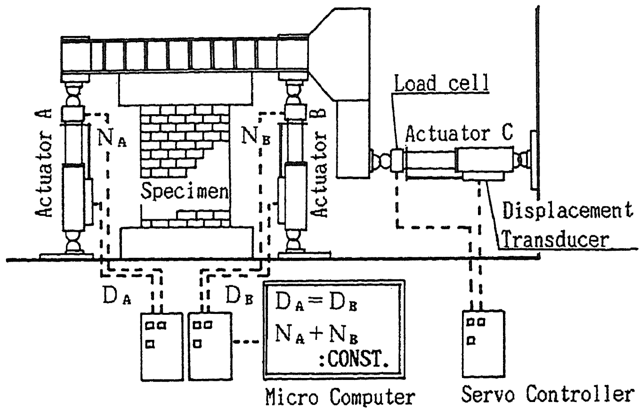

Fig. 3 Test Setup

Loading Rule In principle, horizontal load was applied to each specimen in the following manner; 1) one cycle to the displacement corresponding to the elastic limit, 2) two cycles to the drift angle(R) of 1/400 rad., 3) two cycles to 1/200 rad. and 4) the final two cycles to 1/100 rad.

TEST RESULTS AND DISCUSSIONS

Effect of Shear Reinforcement There are two pairs of specimens to study the effect of the amount of shear reinforcement. The ratio of shear reinforcement was 0.167 percent for GS2 and 0.333 percent for GS3. It was 0.222 percent for GSR1 and 0.697 percent for GSR2. Envelope curves of the nominal shear stress($\bar{\tau}$) versus drift angle relationship for GS2 and GS3, GSR1 and GSR2 are shown in Figs. 4 and 5, respectively.

There is no difference between GS2 and GS3 in the maximum shear strength, but, after the drift angle is more than 1/200 rad., there is significant difference. The two specimens showed diagonal tension crack at approximately same drift angle, from R=1/300 rad. to 1/200 rad.; so it is seemed that there is no difference in the maximum shear strength. The amount of shear reinforcement affected the behavior of the specimen after the diagonal tension crack occurred. Specimen GS3 which have a large amount of shear reinforcement than GS2 maintained its maximum strength till R=1/100 rad., while GS2 lost its strength immediately after the diagonal crack occurred. When the drift angle is 1/100 rad., the shear strength of GS2 is lower by 14 and 53 percent than GS3 in the positive and negative directions respectively.

Specimens GSR1 and GSR2 had the same tendency as GS2 and GS3. Diagonal tension cracks occurred at from R=1/400 rad. to 1/300 rad., and at that time, GSR1 reached its maximum shear strength and couldn't maintain that strength in farther deflection. The shear strength of GSR2 increased until R=1/130 rad. after the diagonal crack occurred, and at that time, compressive failure occurred at the critical compression potions, which resulted in the reduction of the shear strength.

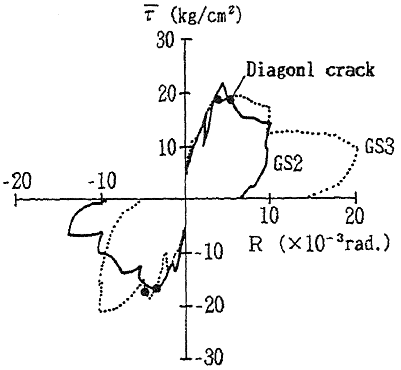

Fig. 4 $\bar{\tau}$ - R relationship(GS2,GS3)

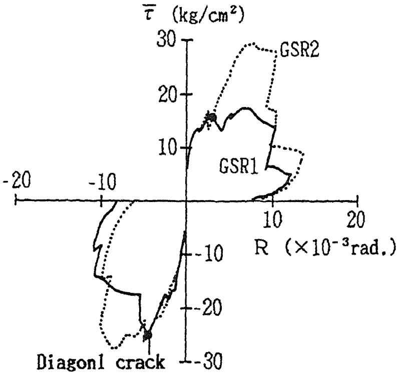

Fig. 5 $\bar{\tau}$ - R relationship(GSR1,GSR2)

Effect of Shear-Span Ratio There is a pair of specimens to study the effect of different shear-span ratio(M/Qd), which was 0.68 for GS2 and 1.14 for GS4. Envelope curves of the nominal shear stress versus drift angle relationship for GS2 and GS4 are shown in Fig. 6.

In GS2 specimen, a diagonal tension crack occurred at maximum shear strength, while GS4 had maximum shear strength after the shear crack occurred within the region of 1.5 times the beam depth from the beam end. Diagonal tention crack did not developed in GS4.

Calculated maximum shear strength of GS2 and GS4 agreed with the corresponding test value. The effect of the shear span ratio on the maximum shear strength seems to be estimated properly in Eq. (1) (See Table.3 note).

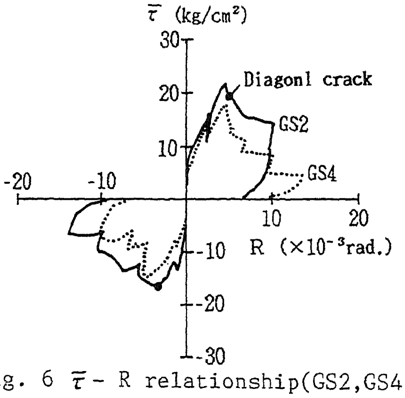

Fig. 6 $\bar{\tau}$ - R relationship(GS2,GS4)

Effect of R/C Slab Envelope curves of the nominal shear stress versus drift angle relationship of GF2(beam with R/C slab) and GF3(rectangular beam) are shown in Fig. 7, and those of GS1(beam with R/C slab) and GS2(rectangular beam) are shown in Fig. 8.

Specimens GF2 and GF3 showed flexural failure, which reached their yield deformation at about R=1/400 rad. and maximum shear strength at from R=1/200 rad. to 1/100 rad. The maximum shear strength of GF2 was 1.69 times as much as that of GF3. Specimen GF2 maintained its calculated strength till R=1/50 rad., but GF3 could maintain its calculated strength only up to R=1/100 rad.

Specimens GS1 and GS2, a pair of short span beams, reached their maximum shear strength at R=1/250 rad. The maximum strength of GS1 was 1.38 times as much as that of GS2. Specimen GS2 could not sustain its maximum strength after R=1/250 rad. and deterioration of the strength was severe, while GS1 maintained its calculated strength till R=1/50 rad.

Specimen GF1, a short span(1.2m) beam with R/C slab, reached its yield deformation at from R=1/400 rad. to 1/300 rad. and maximum shear strength at from R=1/200 rad. to 1/100 rad. This specimen maintained 0.9 times its calculated strength till R=1/50 rad.

The inner(near the beam face) reinforcing bar in the R/C slab reached tensile yield strain during the loading cycle of R=1/400 rad., while outer one did during R=1/200 rad. cycles. In short span beams with R/C slab(GF1 and GS1), all reinforcing bars in the R/C slab reached the tensile yield strain at the large deflection ; i.e. the drift angle was more than 1/100 rad.

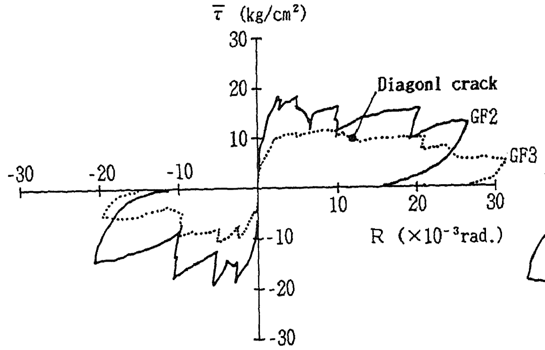

Fig. 7 $\bar{\tau}$ - R relationship(GF2,GF3)

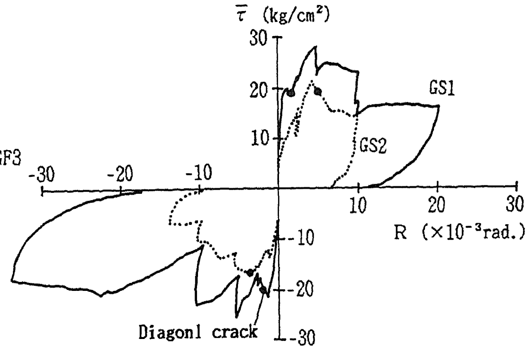

Fig. 8 $\bar{\tau}$ - R relationship(GS1,GS2)

Comparison between Experimental and Calculated Results Comparison between the experimental and the calculated results are listed in Table 3. The calculated results were obtained by Eqs. (1) and (2) (See Table 3 note). These equations are used to estimate the shear and flexural strengths of R/C beams and are specified in A.I.J. R/C Design Standards.

As for the flexural strength, the experimental results are from 1.16 to 1.26 times the calculated results, and on the shear strength, the experimental results are from 0.98 to 1.09 times the calculated results. The shear strength of GS1(the beam with R/C slab) is 1.45 times the calculated strength without the effect of the R/C slab. This experimental strength is found to be equal to the calculated strength of a rectangular beam which has the same depth and cross sectional areas as a T-shape beam with a 43cm wide overhang on each side of the beam.

The initial stiffness obtained from experiment are from 61 to 87 percent for the rectangular beams, from 80 to 153 percent for the beams with R/C slab as compared with the calculated stiffness. In the computation, the effective slab width 12cm for GF1 and GS1, 20cm for GF2 was taken to be the values specified in the A.I.J. R/C Design Standards.

CONCLUSIONS

The following conclusions were obtained.

(1) The shear strength of rectangular masonry beams can be estimated by the equation specified for R/C beam.
(2) The shear strength of the masonry beam with R/C slab is 1.45 times that estimated by Eq. (1) without considering the effect of the R/C slab.
(3) The flexural strength of masonry beams can be estimated as 1.2 times the value calculated by Eq. (2).
(4) The masonry beam with R/C slab sustained larger force than the estimated strength till the drift angle of 1/50 rad.
(5) As for the rectangular masonry beam which have little shear reinforcement(<0.222%), diagonal cracking occurred at the drift angle of

1/300 to 1/200 rad., and after this drift angle, the strength was severely deteriorated. On the rectangular masonry beams which have large amount of shear reinforcement (>0.333%), the deterioration of strength was not severe even after the diagonal crack occurred.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the members of Technical Coordinating Committee on Masonry Research.

Table 3. Test Results

Specimen	Calculated: Flexural strength ① $c\bar{\tau}_{mu}$	Calculated: Shear strength ② $c\bar{\tau}_{su}$	③ ②/①	Test results: Max. shear stress ④ $t\bar{\tau}_{max}$ +	④ −	Test results: Drift angle ⑤ tR +	⑤ −	Test/Calculated: Flexural ⑥ *④/①	Test/Calculated: Shear ⑦ *④/②
GF1	21.32	18.12	0.85	25.54	24.10	9.68	4.96	1.16	1.37
GF2	15.58	14.73	0.95	18.43	19.10	5.14	5.70	1.20	1.27
GF3	8.84	15.38	1.74	11.69	10.52	9.17	5.08	1.26	0.72
GS1	39.51	18.46	0.47	27.98	25.54	4.68	5.43	0.68	1.45
GS2	27.89	18.32	0.66	21.95	16.96	4.32	3.41	0.70	1.06
GS3	27.98	20.53	0.73	20.29	21.52	5.00	9.58	0.75	1.02
GS4	16.92	16.80	0.99	17.75	15.12	4.60	4.48	0.97	0.98
GSR1	28.09	21.25	0.76	17.46	25.59	6.77	4.29	0.77	1.01
GSR2	27.94	26.23	0.94	29.49	27.84	7.53	8.16	1.03	1.09

*④ : Average value

① $c\bar{\tau}_{mu}$: Calculated flexural strength (kg/cm^2)

$c\bar{\tau}_{mu} = Q_{mu}/bD$

$Q_{mu} = 0.9 a_t \sigma_y d (2/\ell)$ -- Eq.(2)

② $c\bar{\tau}_{su}$: Calculated shear strength (kg/cm^2)

$c\bar{\tau}_{su} = Q_{su}/bD$

$Q_{su} = \{0.053 P_t^{0.23} (F_m'+180)/(M/Qd+0.12)+2.7\sqrt{P_w \sigma_{wy}}\}\, bj$ -- Eq.(1)

④ $t\bar{\tau}_{max}$: Maximum shear stress of test (kg/cm^2)

⑤ tR : The drift angle at the maximum strength (x10^{-3} rad.)

where at : cross sectional area of main reinforcement (cm^2)
D : beam depth (cm)
d : effective beam depth (D-dc) (cm)
dc : covering depth (cm)
b : beam width (cm)
ℓ : clear span of beam (cm)
M/Qd: shear span ratio $1 \leq M/Qd \leq 3$
Pt : main reinforcement ratio (100 at/bD) (%)
Fm' : prism compressive strength (kg/cm^2)
Pw : shear reinforcement ratio
σwy : yield strength of shear reinforcement (kg/cm^2)
j : 7d/8 (cm)

(from A.I.J. R/C Design Standards)