0833

ELASTIC-PLASTIC BEHAVIOR OF BUILDING STEEL FRAME WITH STEEL BEARING WALL WITH SLITS

Toko HITAKA[1], Chiaki MATSUI[2], Keigo TSUDA[3] And Yoshihide SADAKANE[4]

SUMMARY

Steel Baring Wall with Slits has been proved to be an earthquake-resisting element with high energy absorption capacity through experiments, and the design formulae we proposed showed good agreement to the test results.

Those experiments, however, had focused on the wall's behavior under an idealized boundary condition; the upper and the lower edge of the wall keeping lateral, thus allowing the deflection point rest at the mid height of the wall. In this paper, the experiment on the steel building frame with steel bearing wall with slit is shown. The beam to column rigidity ratio and the strength/stiffness of the wall are the test parameter; two kinds of frame, one with beam-column rigidity ratio larger than 1 and the other, less than 1, and two kinds of bearing wall, one of which stronger and stiffer than the other. Four frames with the bearing wall and two frames without the wall were subjected to cyclic horizontal load.

The horizontal force that the frame bears did not differ whether the bearing wall is installed or not. The strength of the wall and the stiffness of the wall with moderate stiffness, were nearly as large as in the former test under the idealized boundary condition. The stiffness of the wall with large stiffness, on the other hand, decreased substantialy from that observed in the former test, of which the effect of the beam's deformation is suspected to be the cause. As to the system's energy absorption capacity, the bearing wall greatly contributed to the increment of it.

This paper aims to make clear the behaviors and the mutual effects of the wall and the frame when attached to each other, and to check the applicability of the proposed design formulae.

INTRODUCTION

The steel bearing wall with slits, which is an earthquake-resisting element for building structures, has three remarkable features; 1) ductile behavior, 2) simple evaluating and adjustment method of the strength and the stiffness, and 3) simple fabrication process. The feature 2) is attributed to the parts between the slits of the plate (Column parts, see Fig. 1), behaving like columns. This allows the strength of the wall to be evaluated as the horizontal bearing force when the upper and lower edge section of each Column part is full plastic bending moment. The stiffness of the wall is properly evaluated by taking into consideration the shear deformation of the wall plate, and the bending deformation of the Column parts. The strength and stiffness of the bearing wall with slits, therefore, can be changed independently by simply changing the length, interval length or story number of slit layers.

We have already conducted multiple experiments on the bearing wall (refereed to as "Previous test" here after), made clear the behavior, and proposed the design formulae, the strength and the stiffness of the wall calculated with which showed good agreement with those acquired in the Previous tests [1]. Those tests, however, were

[1] *Graduate School of Human Environment Studies, Kyushu University, Fukuoka, Japan Email:1-1tar@mbox.nc.kyushu-u.ac.jp*
[2] *Graduate School of Human Environment Studies, Kyushu University, Fukuoka, Japan Email:1-1tar@mbox.nc.kyushu-u.ac.jp*
[3] *Graduate School of Human Environment Studies, Kyushu University, Fukuoka, Japan Email:1-1tar@mbox.nc.kyushu-u.ac.jp*
[4] *Graduate School of Human Environment Studies, Kyushu University, Fukuoka, Japan Email:1-1tar@mbox.nc.kyushu-u.ac.jp*

conducted on the bearing wall installed directly in the experiment apparatus, without the surrounding frame and the boundary condition in this test was an idealized one; the upper and lower edge line of the bearing wall would keep horizontal while the specimen deformed .

We thus carried out an experiment on the structure, which is steel frame with the bearing wall (refereed as “Frame test”). In this paper, we explain the details of the experiment, and then with the test results, discuss the mutual effects of the bearing wall and the frame. In the following, “structure” means the frame with/without wall, while “frame” and ”wall” mean frame part and wall part of the structure.

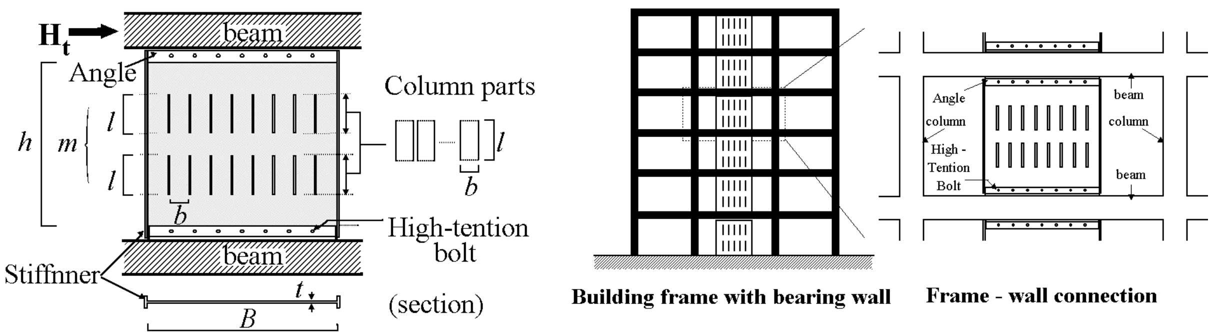


Fig.1 Steel bearing wall with slits

TEST PREPARATION TEST SPECIMEN DESIGNS

Test Specimen Designs:

Specimens of 1/3 – 1/4 the realistic size, 6 in total, were tested under cyclic horizontal load. The test parameters were 1)beam to column rigidity ratio, and 2)strength and stiffness of bearing, as shown in Table 1. As to the bearing wall, two kinds of the bearing walls (refereed as W102 and W202 in the following text and specimen names) tested in the Previous test were prepared, whose properties shown in Table 1.

The previous test has shown that the strength (Q_{wa}) and the stiffness (K_{wa})of the steel bearing wall with slits under the idealized boundary condition, are prescribed by the following equations (1) and (2),

$$Q_{wa} = \frac{M_p}{l/2} \cdot n = \frac{ntb^3}{2l} \cdot \sigma_y \tag{1}$$

$$K_{wa} = \frac{1}{\dfrac{\kappa(h - ml)}{GBt} + \dfrac{\kappa l}{Gbt} \cdot \dfrac{m}{n} + \dfrac{l^3}{Etb^3} \cdot \dfrac{m}{n}} \tag{2}$$

where M_p : full plastic moment of the Column part section, m: number of slit layers (m=2 in the case of Fig.1), n: number of Column parts (n =9 in the case of Fig.1), σ_y : yield stress of the wall plate, κ:shape factor (=1.2), G: shear modulus, E: Young’s modulus and b, l, h, t and B as shown in Fig. 1. Eqs. (1) and (2) show that the strength and the stiffness of the wall change according to b and l of the wall.

Fig. 2 shows an example of the specimens. The bearing wall detail is the same as in the Previous test, with 50 mm breadth and 4.5 mm thickness stiffeners welded at both sides of the wall to restrain the out-of-plane deformation of the wall, which proved effective in the Previous test. Some equipment is attached to the top of columns to suppress out-of-plane deformation of the frame. Each specimen is subjected to cyclic incremental horizontal load (H_t) by hydraulic jack.

Table 1: Test parameters.

Specimen	Parameter			
	Frame	Wall		
	K_b/K_c	m	b (mm)	l (mm)
F100W000	0.531	-	-	-
F100W102		2	41.5	235
F100W202		2	86.0	168
F148W000	1.41	-	-	-
F148W102		2	41.5	235
F148W202		2	86.0	168

K_b/K_c : beam to column rigidity ratio,
m: number of slit layers, b and l :breadth and length of column part (see Fig.1).

Table 2: Material properties.

Test Piece			σ (MPa)	σ (MPa)	ε_u (%)	Y
PL45（Bearing Wall）			290	459	27.1	0.63
Column & F100's Beam	H-100x100x6x8	Flange	319	435	24.2	0.73
		Web	338	449	27.0	0.75
F148's Beam	H-148x100x6x9	Flange	336	480	26.4	0.70
		Web	375	506	20.9	0.74

σ_y: yield stress, σ_u: ultimate stress, ε_u: ultimate strain, Y: yield ratio.

The measurement detail (displacement transducers and strain gages) is also shown in Fig.2. Story deflection angle (R) is defined equal to δ/h_f

Gages on columns measure the deflection ratio, and thus the bending moment of the columns at each section, which then give the frame's bearing horizontal force (Q_f). Wall's bearing horizontal force (Q_w) is defined as the difference between H_t and Q_f. Gages on the beam are for measurement of bending moment of beams

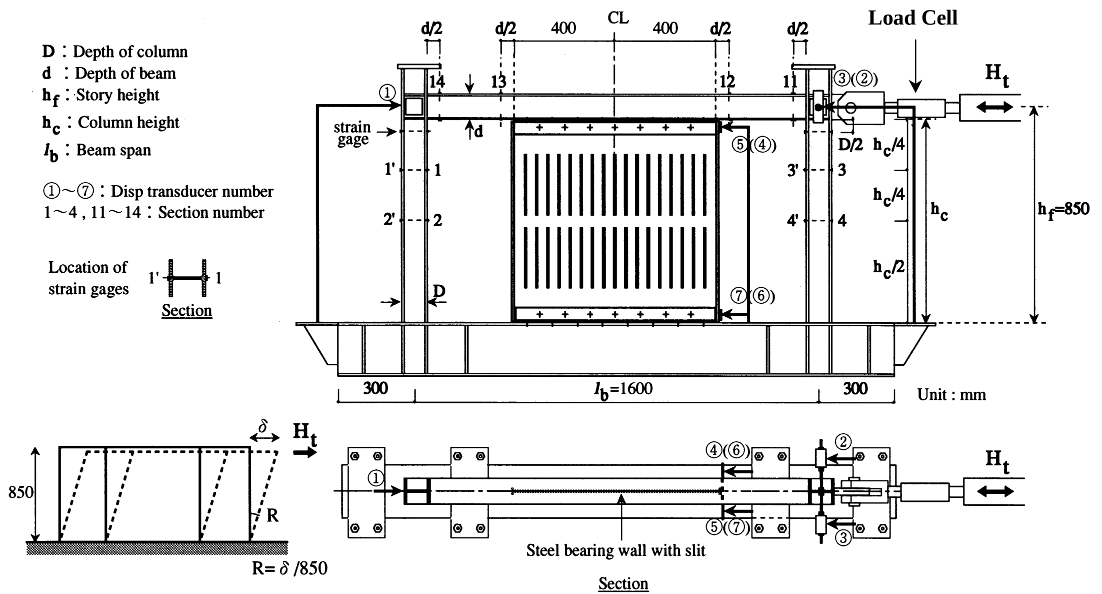
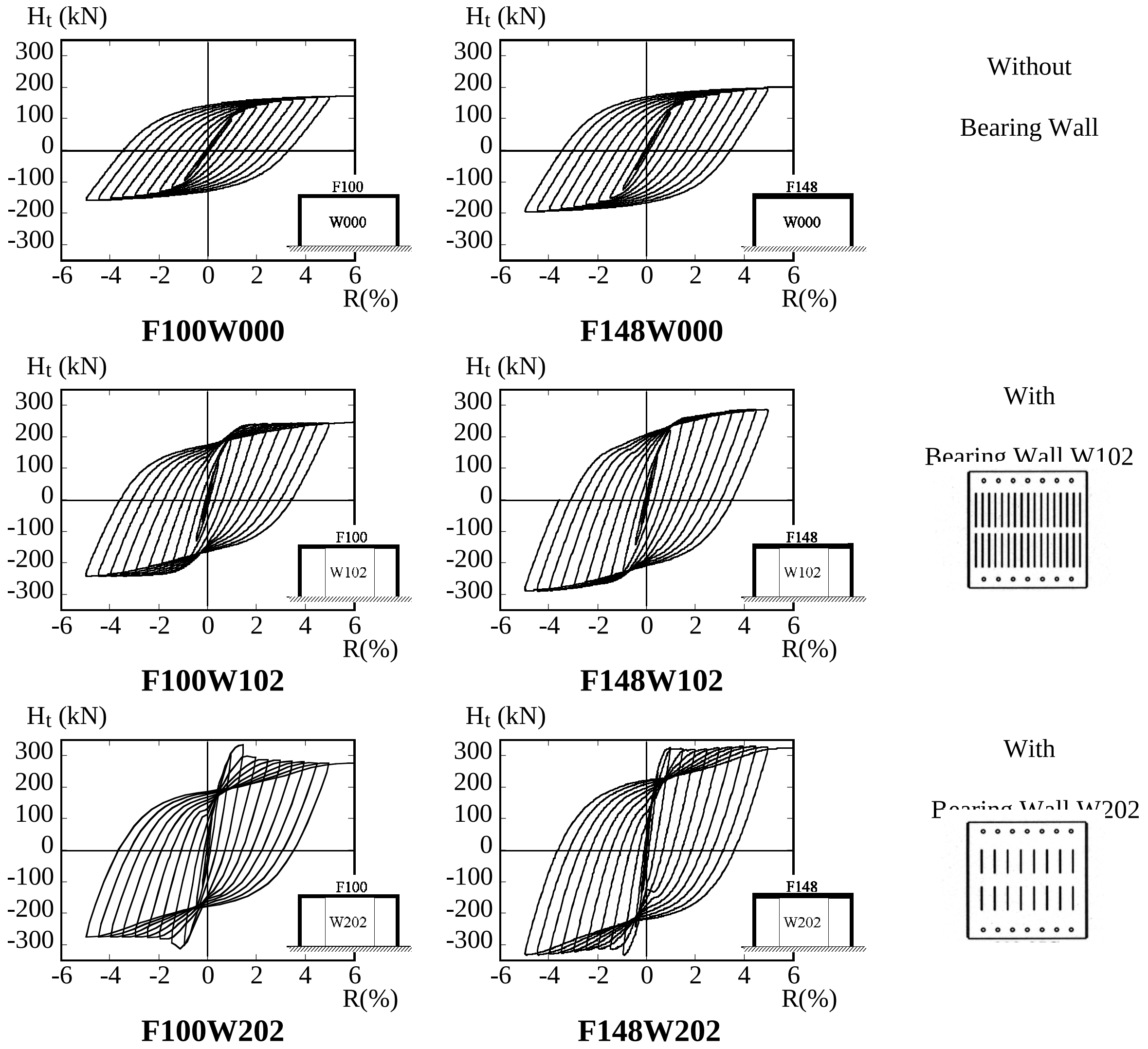


Fig. 2 Example of specimens



ig. 3 Horizontal Load (H_t)-Story deflection Angle (R) Relations.

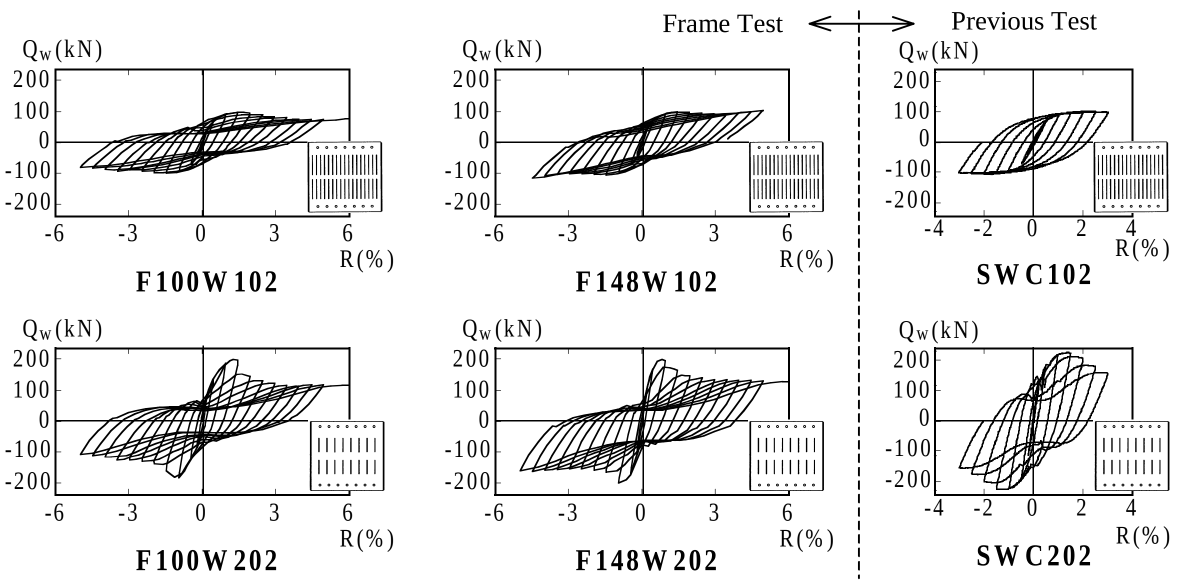


Fig. 4 Wall's Bearing Force (Q_w) –R Relations.

TEST RESULTS

Behavior:

Fig.3 shows the structures' horizontal load (H_t) – story deflection angle (R) relations acquired in this experiment. Fig.4shows the relations between the bearing force of the wall (Q_w) and R, as well as the Q_w – R relations of the bearing walls acquired in the Previous test (without surrounding frame), for comparison.

All figures show ductile behaviors of specimens. The relations between the bearing force of the frame (Q_f) and R do not differ much to each other (the figures of which are thus not shown here.)

As the deformation proceeds, the bearing wall starts to deform out of plane, and at later stage, the stiffeners start to deform out of plane, which is when Q_w reaches its peak. No noticeable differences in behavior are observed when the walls installed in different frame were compared.

From Fig. 5, it is learned that the behaviors of the bearing walls in frame are relatively unstable, compared to those acquired in the Previous test, where the wall was attached to the loading beam whose stiffness was far larger than beams in Frame test. This is suspected due to this difference in upper-lower edge boundary conditions of the bearing wall between Frame test and Previous test.

Strength:

Experimental and theoretical strengths are shown in Table 3. Experimental strength is the maximum horizontal force while story deflection angle (R) is less than 2.0(%). Table 3 shows the results of Frame test, as well as its comparison with the Previous test result and the strength calculated with Eq.(1).

Frame's strength (Q_{fe}) of the specimens were the same whether the structure is without wall, with W102 or with W202. The bearing wall's strengths in the Frame test (Q_{we}) roughly equaled to those of the walls without frame (Q_{wie}), as well as to the analytical strength (Q_{wa}).

Table 3: Strengths.

Specimens	H_{te} (kN)	Q_{fe} (kN)	Q_{we} (kN)	H_{te}/Q_{fie}	Q_{fe}/Q_{fie}	Q_{we}/Q_{wie}	Q_{we}/Q_{wa}	$H_{te}/(Q_{fp}+Q_{wa})$
F100W000	135	135	-	1.00	1.00	-	-	1.05
F100W102	236	139	99	1.75	1.03	1.01	1.13	1.04
F100W202	334	141	207	2.48	1.04	0.92	0.78	0.95
F148W000	160	159	-	1.00	1.00	-	-	1.24
F148W102	259	161	100	1.63	1.01	1.02	1.14	1.13
F148W202	321	175	202	2.02	1.10	0.90	0.76	0.91

H_{te}, Q_{fe}, Q_{we}, Q_{fie}: experimental maximum bearing horizontal force while story deflection angle (R) less than 2.0(%), of structure, frame, bearing wall and structure with no wall, respectively, Q_{wie} :maximum bearing horizontal force of bearing wall in Previous experiment with R less than 2.0(%), Q_{wa}: theoretical strength of bearing wall, given by Eq.(1), Q_{fp}: calculated horizontal strength of frame assuming that the plastic hinges are formed at the upper and lower ends of the column .

Stiffness:

Experimental and theoretical stiffness are shown in Table 4. Experimental stiffness is acquired from the horizontal load – displacement (d) relation of the first loading cycle. Table 4 shows the results of Frame test, as well as its comparison with the Previous test result and the stiffness calculated with Eq.(2).

Comparison of stiffness of structure with wall and without wall (K_{te}/K_{fie}) shows that the wall contributes greatly to increase the stiffness of the structure. There's some modest increase of the frame stiffness (K_{fe}) when the wall is attached to the frame, which is relatively larger as the attached wall's stiffness is larger. As to the wall, unlike the strength, substantial degradation of stiffness occurred in case of specimens with W202 wall.

The main difference between Frame test and Previous test concerning the wall, is the boundary condition, namely the rigidity of upper beam. In case of Previous test, the beams were extremely rigid and forced to move lateral to each other, which kept the deflection point of the wall stay at the mid-height while loading.

During deformation, wall is subjected to the vertical force transferred from frame beam, which is assumed to be roughly as same as the concentrate force P shown in Fig.5. Beam's stress state of the structure with wall (Fig.5 (a)) is considered to be the superposition of stress state of (b) and (c) in Fig 5. As the story deformation of frame caused by P is not large, M_w (difference between bending moments at both side edges of the wall caused by P) is considered roughly equals to the difference between ΔM_f and ΔM (difference between bending moments at both side edges of the wall in case of the structure without wall and the structure with wall, respectively) at the same story deformation angle level. The relation between P and M_w in Fig.5 is described by the following equation (3),

$$\boldsymbol{P} = \frac{1+6\boldsymbol{K_b}/\boldsymbol{K_c}}{(\boldsymbol{x}^2+1)+12\boldsymbol{K_b}/\boldsymbol{K_c}} \cdot \frac{4}{\boldsymbol{x}} \cdot \frac{\boldsymbol{M_w}}{\boldsymbol{l_b}} \tag{3}$$

where K_b / K_c : beam to column rigidity ratio, and other parameters shown in Fig.5. Assuming the same stress transfer system in case of Previous test, the vertical force transferred between wall and beam, P_i is described by the following equation (4),

$$\boldsymbol{P_i} = \frac{\boldsymbol{Q_w} \cdot (\boldsymbol{h_w}/2)}{\boldsymbol{x l_b}} \tag{4}$$

where Q_w: horizontal bearing force of the wall, h_w: height of wall (=800mm).

With the data of bending moment at beam sections 11-14 in Fig.2 , derived from strain data, M_w when story deformation angle R=0.25(%) and 0.5(%) was calculated and applied to Eq.(3). The result (P) is shown in Table 5. P_i , as well, was calculated with Eq.(4), where Q_w is the bearing wall's bearing horizontal force when R=0.25(%) and 0.5(%) in the Previous test as well. Table 5 also shows comparison of P and P_i (P / P_i).

From Table 5, it is observed that compared at the same story deformation level, the vertical force transferred from beam to wall in Frame test (P) is smaller than that in Previous test (P_i). The reason for this is considered that the beam in case of Frame test is not solid enough that the beam's bending deformation attributed to P is negligible, while it is, in case of Previous test.

Table 4: Stiffness.

Specimen	K_{te} (kN/mm)	K_{fe} (kN/mm)	K_{we} (kN/mm)	K_{te}/K_{fie}	K_{fe}/K_{fie}	K_{we}/K_{fe}	K_{we}/K_{wie}	K_{we}/K_{wa}
F100W000	14.0	14.0	-	1.00	1.00	-	-	-
F100W102	39.2	14.8	24.4	2.79	1.06	1.64	0.86	0.94
F100W202	69.9	16.9	52.9	4.98	1.21	3.12	0.47	0.48
F148W000	16.0	16.0	-	1.00	1.00	-	-	-
F148W102	42.4	17.8	24.5	3.02	1.12	1.37	0.87	0.94
F148W202	81.7	19.2	62.5	5.82	1.20	3.26	0.56	0.57

K_{te}, K_{fe}, K_{we}, K_{fie} : experimental stiffness of structure, frame, bearing wall and the structure without wall, respectively, K_{wie} : experimental stiffness of bearing wall in Previous test, K_{wa} : theoretical stiffness of bearing wall, calculated by Eq.(2),

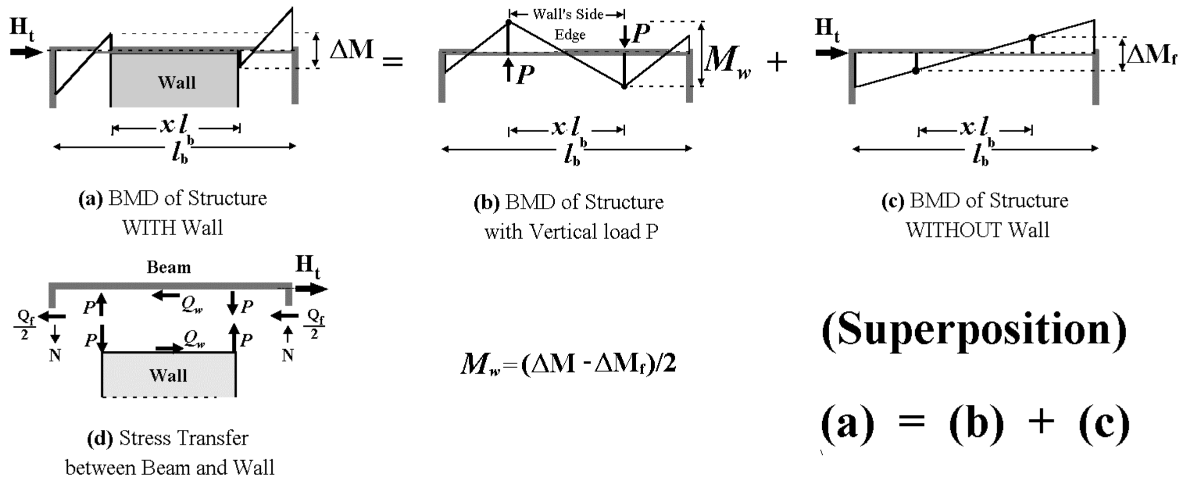


Fig. 5 Stress Transfer between Wall and Frame.

Table 5: Vertical Force between Wall and Beam.

Specimen	R=0.25 (%)		R=0.5 (%)	
	P (kN)	P/P_i	P (kN)	P/P_i
F100W102	22.9	0.99	35.1	0.90
F100W202	31.8	0.46	58.9	0.64
F148W102	23.7	1.07	47.1	1.21
F148W202	39.1	0.55	66.7	0.72

P :see Fig.5, P_i : vertical force transferred from beam to wall in Previous test case

Energy absorption capacity:

Based on horizontal load -story deflection angle (R) relations, energy absorbed by structure with wall (Et) and that without wall (Efi) at each loading cycle, were calculated and their ratios are shown in Fig. 6.

Fig.6 shows that the bearing wall contributes to enlarge the energy absorption capacity while defamation is small. Energy absorbed by Frame also is larger if bearing wall is attached to it.

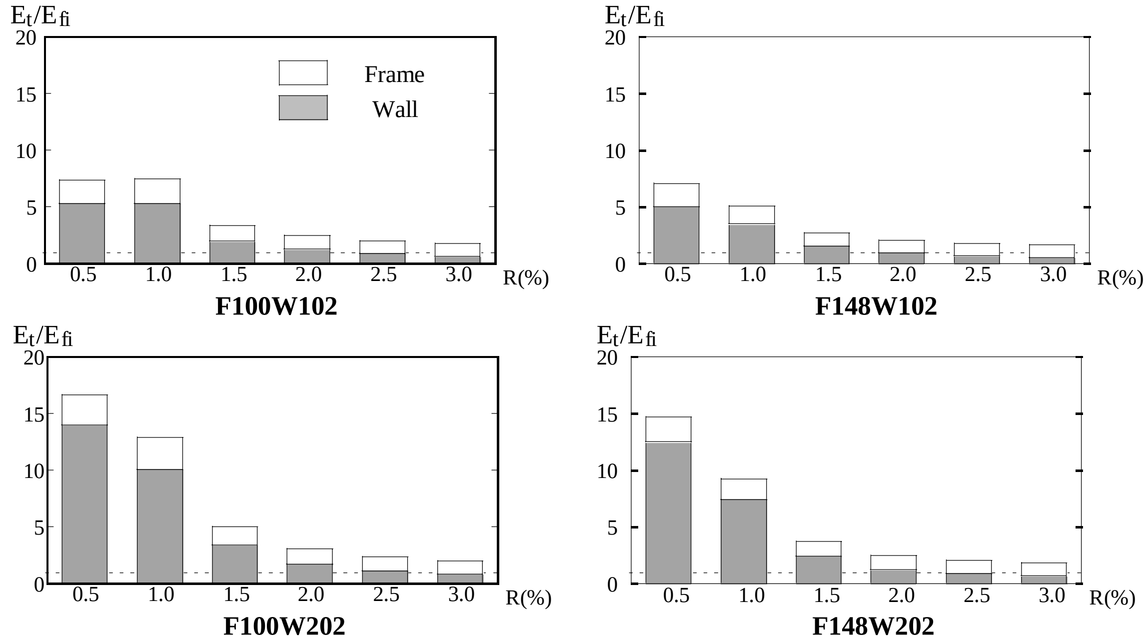


Fig. 6 Energy Absorption Capacity.

CONCLUSIONS

Two steel building frames and four steel building frames with Steel Bearing Wall with slits, both made of normal steel with yield stress about 300 (MPa), were subjected to cyclic horizontal load, to investigate bearing wall's behavior installed in building frame, and mutual effect between frame and wall. Test parameters were beam-to-column rigidity ratio, and strength and stiffness of Steel Bearing Wall with Slits. Along with the result of Previous test, where bearing walls whose sizes and design are same as those in this test (Frame test) , Frame test gave the following conclusions;

1. All structures behave ductile whether wall is attached or not.

2. Frame's strength and stiffness of structure with wall do not differ from that of frame with no wall attached to it.

3. Influence of frame's performance to bearing wall's strength is small, and the proposed formula to prescribe strength of bearing wall is appropriate.

4. Vertical force transferred from bearing wall to beam differs eminently between the Frame test case and Previous test case.

5. Energy absorption capacity while relatively small story deformation, is largely enhanced by installing bearing wall.

REFERENCES

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