SEISMIC ENERGY DISSIPATION SYSTEM OF 12-STOREY COUPLED SHEAR WALLS

Makoto KATO[1], Masaomi TESHIGAWARA[2], Ken-ichi SUGAYA[3] And Yoshiyuki MATSUSHIMA[4]

SUMMARY

The U.S.-Japan cooperative earthquake research project on composite and hybrid structures have conducted from 1994 for 5-years. A building with center core reinforced concrete walls and exterior steel frame was selected as a target building for Hybrid Wall System (HWS). The flange part of each wall of the coupled shear walls can reduce seismic compressive stresses, and hence improve the overall seismic performance of the coupled shear walls. The coupling beams can be designed to absorb the most of the seismic energy as well as the base of the wall, then the coupled shear walls are the primary seismic energy consumption elements.

In order to investigate the seismic performance of the coupled shear walls, the seismic test on 1/3-scale 12-story T-shaped coupled shear walls has been conducted under this research project. According to the seismic test results, the ratio of energy dissipation of the coupling beams was the half mostly to the total energy dissipation. Using the simple analytical model reflecting the tendency of the energy dissipation of the seismic test results, the static and dynamic analyses were conducted to determine the optimum moment capacity distribution between the base of the shear walls and the coupling beams. The factors affecting on the mechanisms of the energy dissipation in the system were the ratio of the rotational angle of the coupling beams to shear walls, the ratio of the yielding rotational angle of the coupling beams to shear walls, and the ductility factor of the coupling beams. And when the moment carrying ratio of the coupling beams to the total over-turning moment is from 0.4 to 0.5, the energy dissipation of the coupling beams that are expected ductile manner until large deformation becomes the most effective.

INTRODUCTION

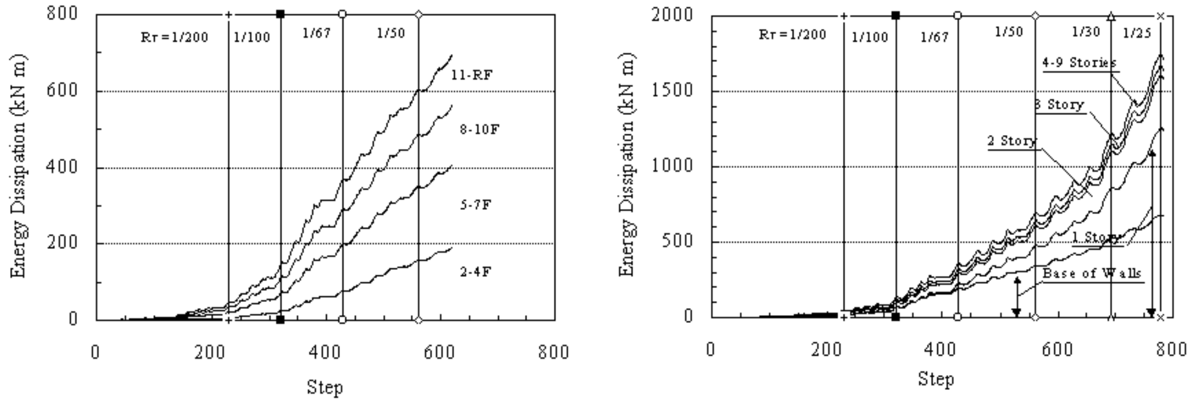
Since it is easy to realize the whole collapse type which forms a plastic hinge in the end of the coupling beams and the base of the coupled shear walls, the RC coupled shear walls system has a high seismic performance on the view point of the energy dissipation. At designing the RC coupled shear walls system, the bending strength ratio of the coupling beams to the coupled shear walls has large influence on the energy dissipation of the system. In the case that the bending strength ratio of the beam to the wall is small, the coupled shear walls system behaves almost as two independent walls. At the large deformation level, although the energy dissipation of the system becomes large, it is expected that the bending deformation of the building becomes large. Conversely, the bending deformation is small in the case that the bending strength of the beam to the wall is large, and the high ductility capacity is required at the wall. Moreover, it is predicated that the bending strength ratio of the beam to the wall affect the seismic responses, such as the maximum drift angle and the maximum rotational angle. The dependence ratio of the bending strength of the beam to the total bending strength of the system (R.S.B.) of the 12-story test [Kato, Sugaya, and Nagatsuka, 1996] specimen was 0.35.

[1] Architectural Design Division, Tobishima Corporation, Tokyo, Japan, E-mail: makoto_kato@tobishima.co.jp
[2] Dept. of Structural Engineering, Building Research Institute, Japan E-mail: teshi@kenken.go.jp
[3] Architectural Design Division, Fudo Construction, Tokyo, Japan, E-mail: k-sugaya@fudo.co.jp
[4] Department of Engineering, Fudo Building Research, Tokyo, Japan, E-mail: ymatsu@fudo.co.jp

This paper discusses on the mechanisms of the energy dissipation of the system using the analysis model in which the energy characteristic of the 12-story test results reflect, and on the rational energy distribution at the design of the system.

ENERGY DISSIPATION CHARACTERISTIC OF 12-STORY TEST

The transition of the energy dissipation of the beam and the wall is shown in Fig. 1. The energy dissipation of the beam increased from the structural drift (=R_T) of 1/200 up to that drift, all of the beam yielded. The energy issipation of the beam in every third floors was almost even. After R_T of 1/200, the energy dissipation of the wall increased according to the yielding of the base of the compression side wall. The amount of energy dissipation by the beam were almost the same as by the wall at R_T of 1/67, although the energy dissipation of the beam had exceeded the wall at the small deformation. In order to clarify the tendency of the energy dissipation, the dependence ratio of the energy of the beam to the total energy of the system (R.E.B.) is studied. The transition of the R.E.B. of the test result is shown in Fig. 2. The R.E.B of the test result went up gradually till R_T of 1/200. The change of the R.E.B. according to the deformation level was not remarkable. Moreover, the R.E.B. of the test specimen were from 0.5 to 0.6 through the test. The R.S.B. of the specimen of the 12-story test was about 0.35.



(a) Coupling Beams (b) Coupled Shear Walls

Fig.1 Transition of Energy Dissipation of Test

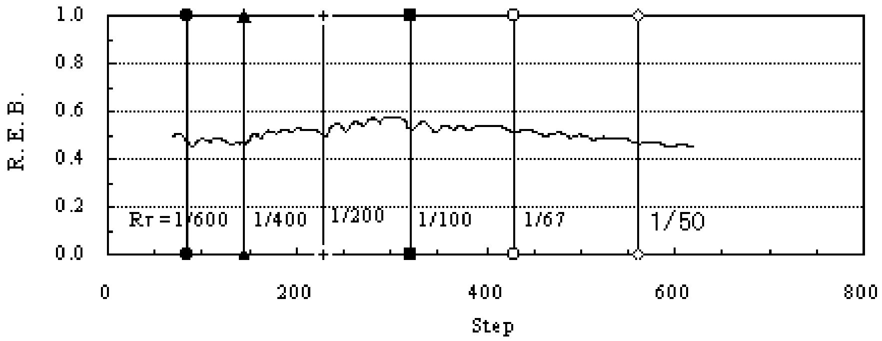
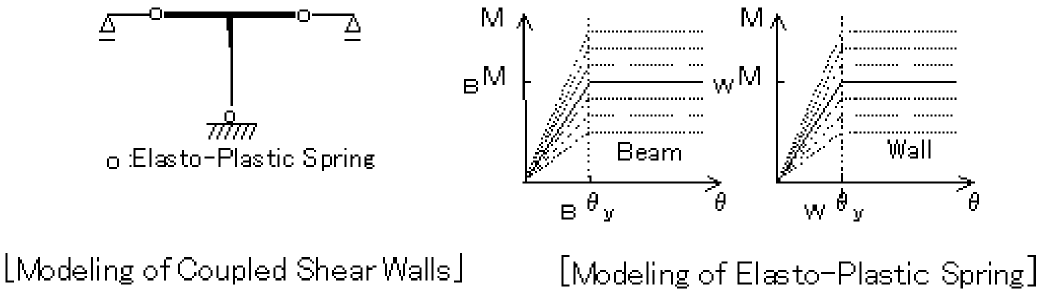


Fig.2 Transition of R.E.B. of Test

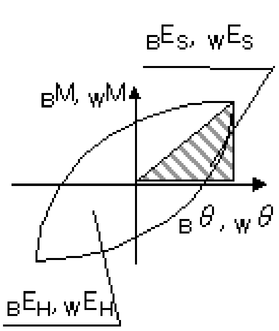
RATIONAL STRENGTH RATIO OF BEAM TO TOTAL STRENGTH RATIO OF HWS SYSTEM

Analytical Model:

In order to determine the rational the R.S.B., the simple wall and beam assembly model that is shown in Fig. 3 (a) is used. This model is based on the test results that the distribution of the energy dissipation of the beam along to the height was almost even, and the energy dissipation of the wall concentrated on the base of the wall in the test. The coupled shear walls system of the 12-story was modeled into the two beams and the wall of one story, and the elasto-plastic spring of the Bi-linear model was provided in the both ends of the beam, and the base of the wall. In addition, in order to make the analyses simple and clear, the yielding rotational angle of the elasto-plastic spring is constant against any the bending strength. The hysteresis energy and the strain energy defined in this paper are shown in Fig. 3 (b).



(a) Analytical Model



$_BE_H$: Hysteresis Energy of Beam

$_WE_H$: Hysteresis Energy of Wall

$_BE_S$: Strain Energy of Beam

$_WE_S$: Strain Energy of Wall

Dependence Ratio of Bending Strength of Beam (R. S. B.)

$_BM / (_BM + \gamma \cdot {_WM})$

Dependence Ratio of Energy of Beam (R. E. B.)

$_BE / (_BE + {_WE})$

Magnification of Strain Energy (M. S. E.)

$(_BE + {_WE}) / (_BM \cdot {_B\theta_y})$

(b) Hysteresis Energy and Strain Energy

Fig.3 Details of Analytical Model

Energy Dissipation:

In order to arrange the relation of the R.S.B. and the tendency of the energy dissipation, the lateral load of one direction was applied to the analytical model. The yielding of the beam precedes to the yielding of the wall in the case that the R.S.B. is small. The case that both of the beam and the wall yielded is assumed. The static strain energy of the beam and the wall ($_BE_S$, $_WE_S$) is expressed with the bending strength of the beam and the wall ($_BM$, $_WM$), the rotational angle and the yielding rotational angle as Eqs. (1) and (2). Here by using the ductility factor of the beam and the wall, the ratio of the rotational angle of the wall to the beam, and the ratio of the yielding rotational angle, the R.S.B. and the relation of the total strain energy presented by Eq. (3). Furthermore, Eq. (4) will be derived from the assumption that the ratio of the rotational angle of the wall to the beam is 1/3, and the ratio of the yielding rotational angle is 1/2. In the case that the ductility factor of the beam is changed from 1.5 to 8, the relation of Eq. (4) is shown in Fig. 4 (a).

$$ {}_BE_S = {}_BM\left({}_B\theta - \frac{1}{2}\cdot{}_B\theta_y\right) \quad \cdots\cdots (1)$$

$$ {}_WE_S = {}_WM\left({}_W\theta - \frac{1}{2}\cdot{}_W\theta_y\right) \quad \cdots\cdots (2)$$

${}_BE_S$: *Strain Energy of Beam*、${}_WE_S$: *Strain Energy of Wall,*

${}_BM$: *Bending Strength of Beam*、${}_WM$: *Bending Strength of Wall*

${}_B\theta$: *Rotational Angle of Beam*、${}_W\theta$: *Rotational Angle of Wall,*

${}_B\theta_y$: *Yielding Rotational Angle of Beam*、${}_W\theta_y$: *Yielding Rotational Angle of Wall*

$$ {}_B\mu = \frac{{}_B\theta}{{}_B\theta_y} \geqq 1, \quad {}_W\mu = \frac{{}_W\theta}{{}_W\theta_y} \geqq 1, \quad \alpha = \frac{{}_WM}{{}_BM} \geqq 0, \quad \beta = \frac{{}_W\theta_y}{{}_B\theta_y} > 0, \quad \gamma = \frac{{}_W\theta}{{}_B\theta} > 0,$$

$$ X = \frac{{}_BM}{{}_BM + \gamma\cdot{}_WM}, \quad Y_1 = {}_BE + {}_WE$$

$$ \frac{Y_1}{{}_BM\cdot{}_B\theta_y} = \left({}_B\mu - \frac{1}{2}\cdot\frac{\beta}{\gamma}\right)\cdot\frac{1}{X} - \frac{1}{2}\left(1 - \frac{\beta}{\gamma}\right) \quad \cdots\cdots (3)$$

if assumes that $\beta = 1/2$、$\gamma = 1/3$,

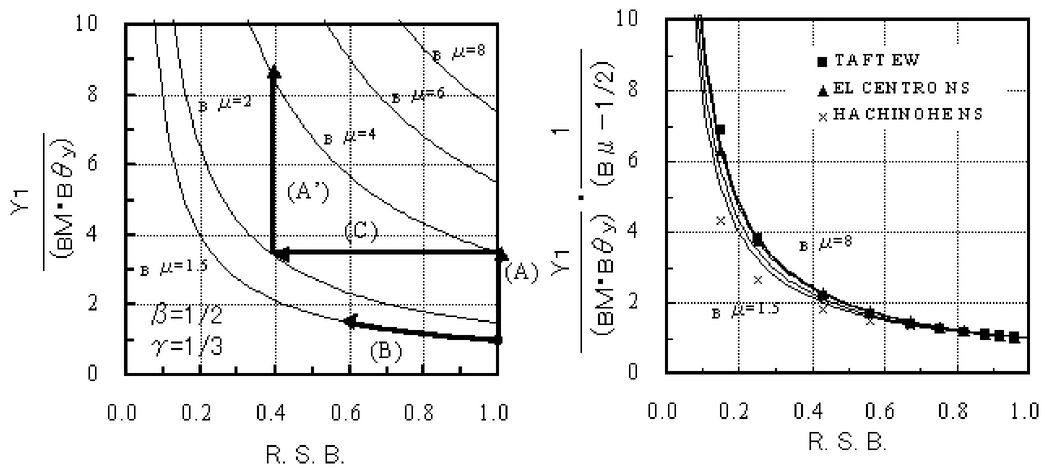
$$ \frac{Y_1}{{}_BM\cdot{}_B\theta_y} = \left({}_B\mu - \frac{3}{4}\right)\cdot\frac{1}{X} + \frac{1}{4} \quad \cdots\cdots (4)$$

from (4) equation

$$ \frac{Y_1}{{}_BM\cdot{}_B\theta_y}\cdot\frac{1}{{}_B\mu - \frac{1}{2}} = \frac{4\cdot{}_B\mu - 3}{2(2\cdot{}_B\mu - 1)}\cdot\frac{1}{X} + \frac{1}{2(2\cdot{}_B\mu - 1)} \quad \cdots\cdots (5)$$

Magnification of Strain Energy:

The vertical axis of Fig. 4 (a) shows the magnification of the elasto-plastic strain energy to the twice elastic strain energy of the beam (M.S.E.). In the case that the R.S.B. is fixed, the energy dissipation required for the total energy increases according to that the ductility factor of the beam becomes large ((A) or (A') line in Fig. 4 (a)). The M.S.E. becomes large according to that the R.S.B. becomes small, in the case that the ductility factor of the beam is fixed (line of (B)). This shows the tendency that the energy dissipation of the wall becomes large compared with the energy dissipation of the beam. The ductility factor of the beam is small, in the case that the R.S.B. becomes small, in the case that the M.S.E. is fixed (line of (C)). In the case that the ductility factor of the beam is changed from 1.5 to 8, the relation of Eq. (5) is shown in Fig. 4 (b) as the solid lines. Equation (5) is



(a) Relation of M.S.E. and R.S.B. (b) Relation of R.M.S.E. and R.S.B.

Fig.4 Magnification of Energy Dissipation

drawn from Eq. (4), and Eq. (5) shows the ratio of the M.S.E. to the M.S.E. at X=1.0 of each ductility factor of the beam (R.M.S.E.). Figure 4 (b) shows that the R.M.S.E. is almost constant to any ductility factor of the beam, and the R.M.S.E. increase in the case that the R.S.B. is smaller than 0.4.

Dependence Ratio of Energy of Beam (R.E.B.) :

The relation between the R.E.B. and the R.S.B. is shown by Eq. (6). Equation (7) is derived from Eq. (6) by assuming the ratio of the yielding rotational angle of the wall to the beam, and the ratio of the rotational angle of the wall to the beam. In the case that the ductility factor of the beam is 1.5, the relation between the R.E.B. and the R.S.B are shown by Eq. (8). Figure 5 (a) shows Eq. (7) , in Fig. 5 (a), the case that the ductility factor of the beam is 1.5 is shown as the solid line, and the case that the ductility factor of the beam is infinity is shown as the dotted line. The relation of the R.S.B. and the dependence ratio of the plastic energy of the beam to the total energy (R.P.B.) is shown in Fig. 5 (b). The R.P.B. is equivalent to the difference of the solid line and the dotted line of Fig. 5 (a). The R.P.B. becomes the largest in the case that the R.S.B. is from 0.4 to 0.5, and this range of the R.S.B. is efficiently on the energy dissipation.

$$Y_2 = \frac{{}_B E}{{}_B E + {}_W E} = \frac{\left(2 \cdot {}_B \mu - \frac{\beta}{\gamma}\right)\left(1 - 2 \cdot {}_B \mu\right)}{\left(\frac{\beta}{\gamma} - 1\right)^2} \cdot \frac{1}{X + \frac{2 \cdot {}_B \mu - \frac{\beta}{\gamma}}{\frac{\beta}{\gamma} - 1}} + \frac{2 \cdot {}_B \mu - 1}{\frac{\beta}{\gamma} - 1} \cdots\cdots (6)$$

if assumes that $\beta = 1/2$, $\gamma = 1/3$,

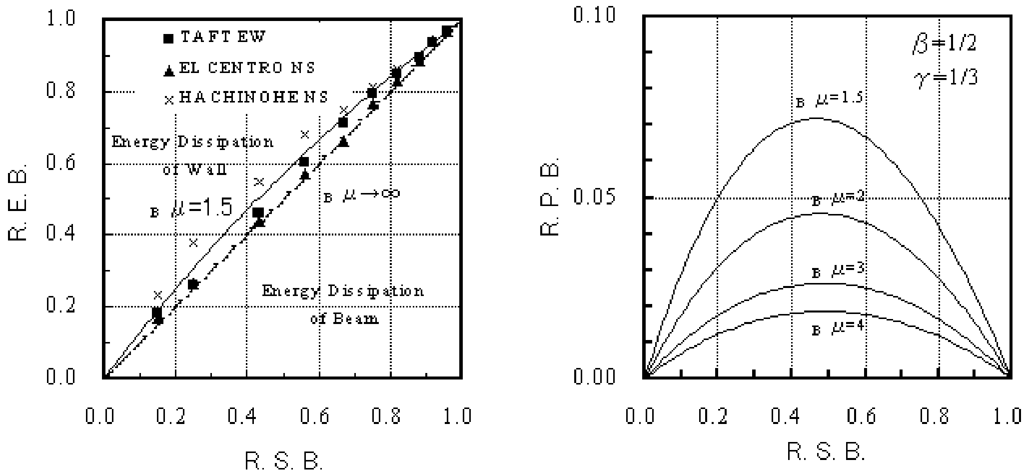
$$Y_2 = 2\left(4 \cdot {}_B \mu - 3\right)\left(1 - 2 \cdot {}_B \mu\right) \cdot \frac{1}{X + 4 \cdot {}_B \mu - 3} + 2\left(2 \cdot {}_B \mu - 1\right) \cdots\cdots (7)$$

from $\frac{{}_W \mu}{{}_B \mu} = \frac{\gamma}{\beta} = \frac{2}{3}, \quad \frac{3}{2} \leq {}_B \mu < \infty$

$$Y_2 = -12 \cdot \frac{1}{X + 3} + 4 \left(when\ {}_B \mu = \frac{3}{2} \right) \cdots\cdots (8)$$

Rotational Angle of Beam and Wall:

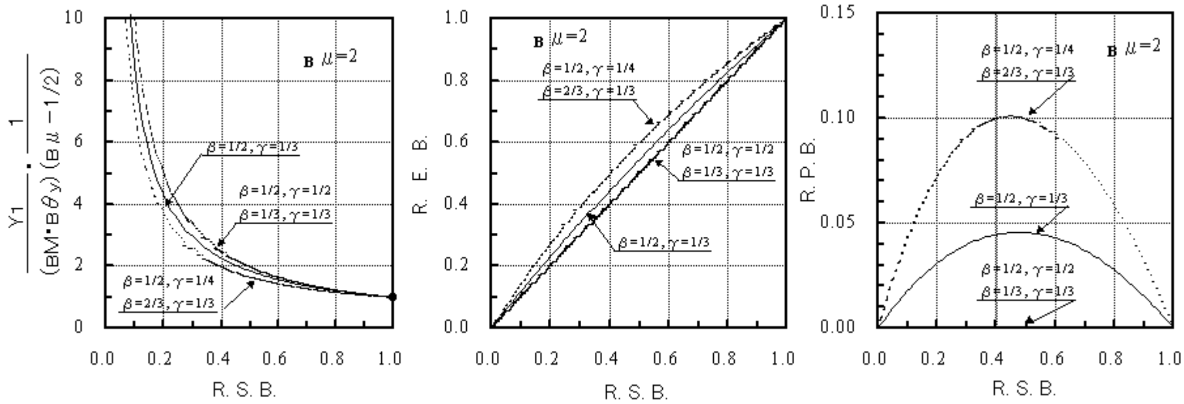
The study on the energy dissipation tendency was performed based on Eqs. (3) and (6). In the case that the ductility factor of the beam is 2, the relation of the R.S.B., R.M.S.E., R.E.B., and R.P.B. is shown in Fig. 6. As shown in Fig. 6 (a), even if the ratio of the rotational angle and the yielding rotational angle of the wall to the beam change, the relation of the R.M.S.E. and the R.S.B. is almost constant. Figure 6 (b) shows that the R.E.B. becomes large in the case that the ratio of the rotational angle is small, the ratio of the yielding rotational angle is



(a) Relation of R.E.B. and R.S.B. (b) Relation of R.P.B. and R.S.B.

Fig.5 Dependence Ratio of Energy Dissipation

large. Figure 6 (c) shows that the R.P.B. becomes the largest, in the case that the R.S.B. is from 0.4 to 0.5, regardless of the ratio of the rotational angle and the yielding rotational angle.



(a) Relation of R.M.S.E. and R.S.B. (b) Relation of R.E.B. and R.S.B. (c) Relation of R.P.B. and R.S.B.

Fig.6 Change of Energy Dissipation on Rotational Angle of Beam and Wall

Response Analysis by Analytical Model:

For verification of the energy dissipation tendency, and the applicability to the real building, the dynamic response analysis was carried out using the analytical model (Q_B=980 kN, C_B=0.3). The horizontal strength, the initial stiffness, and the rotational angle are agreement. By the Bi-linear model for the hysteresis model of the beam and the wall, both equivalent viscous damping factor are same. Therefore, the vertical axis of Fig. 5 (a) and Fig. 6 (a) shows the ratio of the dynamic energy dissipation of the beam and the wall. The input earthquake waves using the dynamic analysis are shown in Table 1. The input level was standard-ized by the max velocity of 50 cm/s. The damping is proportional to the instant stiffness, and the damping factor was 3%. The R.M.S.E. of the dynamic analysis results were shown in Fig. 4 (b). In Fig. 5 (a), the dynamic analysis results were plotted by the marks. Figure 4 (b) and Fig. 5 (a) indicate good correlation between the dynamic analysis results and Eqs. (5) and (7). Therefore the relation of the energy dissipation and the R.S.B. will be considered statically.

Table 1 Input Waves Using Dynamic Analysis

Input Wave	Max Acceleration (cm/s²)	Max Velocity (cm/s)	Continuation Time (sec)	Time Unit (sec)	Number of Data
TAFT 1952 EW	496.8	50.0	54.40	0.02	2720
EL CENTRO 1940 NS	510.8	50.0	53.76	0.02	2688
HACHINOHE 1968 NS	330.1	50.0	36.00	0.01	3600

Rational Dependence Ratio of Bending Strength of Beam:

As shown in Fig. 4 (b) and Fig. 6 (a), in the case that the R.S.B. is smaller than 0.4, the R.M.S.E. becomes large to any the ductility factor of the beam. In the case that the R.S.B. is 0.4, the R.M.S.E. becomes about 2 times, and the energy dissipation of the beam and the wall are equivalent. At this time, as shown in Fig. 5 (b) and Fig. 6(c), the R.P.B. also becomes large. From the above thing, the case that the R.S.B. is from 0.4 to 0.5 will be rational on the energy dissipation.

This paper showed that the energy dissipation tendency on the R.S.B. of the coupled shear walls system could be grasped by the ratio of the rotational angle and the yielding rotational angle of the beam and the wall. Furthermore, even if the relation of the rotational angle and the bending characteristic of the hinge parts of system are different from the assumed conditions, it is clear that prediction on the energy dissipation of the total system is possible by using Eqs. (3) and (6).

CONCLUSIONS

According to the 12-story test results,

1. The energy dissipation of the coupling beams in every third floors was almost even.
2. The energy dissipation of the coupling beams increased from 1/200 when the whole floor yielded.
3. The energy dissipation of the coupled shear walls increased from 1/200 when the base of the compression side wall yielded.
4. The energy dissipation ratio of the coupling beams and the coupled shear walls became almost of the same grade at 1/67, although the energy dissipation of the coupling beams had exceeded the energy dissipation of the coupled shear walls at the small deformation.
5. The dependence ratio of the energy of the beam to the total energy (R.E.B) were from 0.5 to 0.6.

According to the analysis in this paper,

6. The tendency of the energy dissipation can guess the degree of influence using Eqs. (3) and (6) by assuming the ratio of the rotational angle and the yielding rotational angle of the beam and the wall.
7. In the case that the dependence ratio of the bending strength of the beam to the total bending strength (R.S.B.) is from 0.4 to 0.5, the dependence ratio of the plastic energy of the beam to the total strain energy (R.P.E.) becomes the largest.
8. In the case that the dependence ratio of the bending strength of the beam to the total bending strength (R.S.B.) is from 0.4 to 0.5, the coupled shear walls system will be rational on the energy dissipation.

ACKNOWLEDGMENT

This work financially supported by the U.S.-Japan Cooperative Earthquake Research Project on Composite and Hybrid Structures. The authors would like to acknowledge Prof. H. Aoyama, chairman of Technical Coordinating Committee, Prof. A. Wada, chairman of Hybrid Wall System Technical Sub-Committee, Prof. T. Kabeyazawa, and all members of the Project for their useful advises and suggestions.

REFERENCE

M. Kato, K. Sugaya, and N. Nagatsuka (1996), OPTIMUM MOMENT DISTRIBUTION BETWEEN SHEAR WALLS AND BOUNDARY BEAMS OF COUPLED SHEAR WALL WITH FLANGE WALLS , *11th World Conference on Earthquake Engineering*, CD-ROM paper no. 775, Acapulco, Mexico, 8pp.