TORSIONAL RESPONSE OF SINGLE-STORY R/C STRUCTURES WITH BRITTLE MEMBERS SUBJECTED TO STRONG GROUND MOTION

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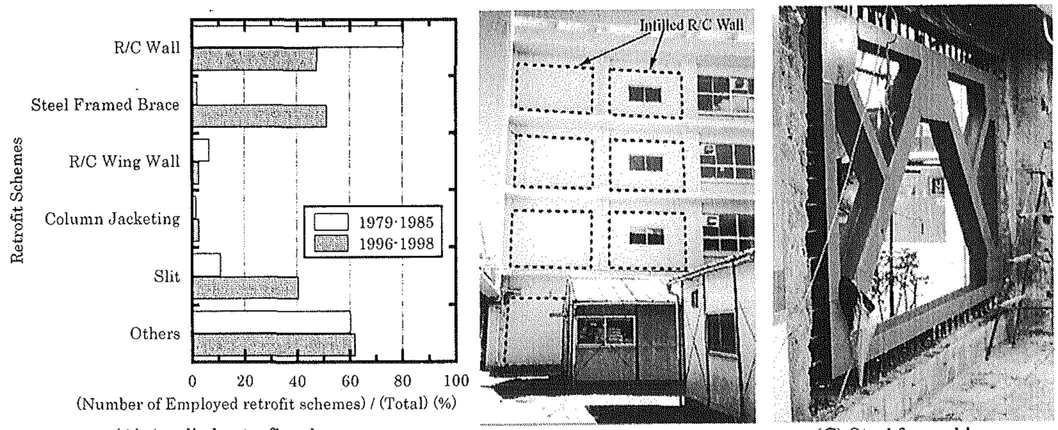
ABSTRACT

In past earthquakes, some buildings were damaged because of unbalanced distribution of shear walls, and some of them had severe shear failures. However few investigations concerning the influence of brittle failure on response of asymmetric structures have been made. In this paper, the influence of brittle failure on torsional response is analytically investigated. The results show that the lateral resistance of asymmetric brittle structures deteriorates significantly than that of symmetric brittle structure, which magnifies that lateral drift of asymmetric brittle structures more significant than symmetric brittle structures, and hence the response of brittle structures is much more sensitive to the unbalanced distribution of members than that of ductile structures.

1. INTRODUCTION

After the 1995 Hyogo-ken Nanbu Earthquake, seismic retrofit of existing R/C buildings designed before 1981 has been widely carried out throughout Japan. In retrofitting an existing R/C building, two general design strategies are usually applied. The one is to improve its strength by adding retrofit member such as R/C walls and/or steel framed braces. The other is to improve its deformation capacity by steel or concrete jacketing. **Fig. 1** compares the trends of retrofit schemes employed in retrofit design in Shizuoka Prefecture, Japan[1]. **Fig. 1(A)** shows that addition of R/C walls (**Fig. 1(B)**) was most widely applied but steel framed braces (**Fig. 1(C)**) were not major schemes in 1980s. **Fig. 1(A)** also shows that although the R/C wall is still widely applied, the steel framed brace is currently rather common scheme in retrofitting existing R/C buildings.

It should be also pointed out that ductility improvement has not been a major scheme, although old Japanese existing vulnerable buildings are generally brittle buildings. In the retrofit design, well-balanced placement of retrofit member in a building is most essential to ensure seismic performance during an earthquake. However, retrofit members might be placed in a building in an unbalanced manner to maintain its architectural function. The response of brittle buildings may be more



(A) Applied retrofit schemes **(B) R/C wall** **(C) Steel framed brace**

Fig. 1 Applied retrofit schemes

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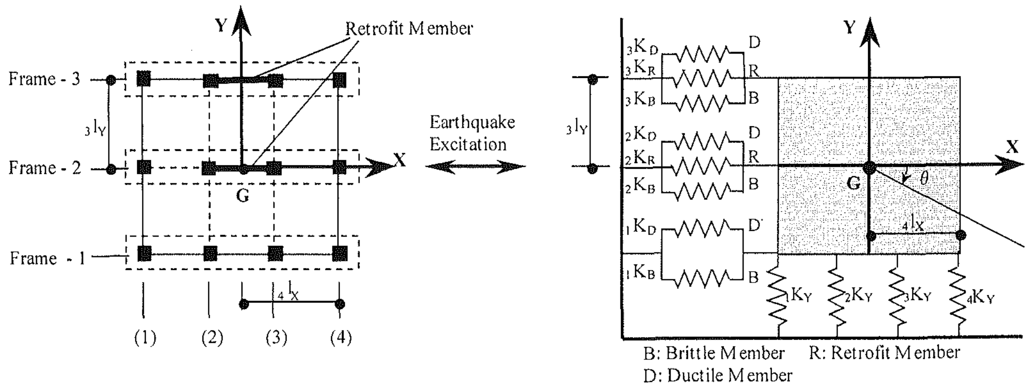
sensitive to the unbalanced distribution of members than that of ductile buildings due to the reason as follows: a torsional response due to the unbalanced distribution of members results in brittle failure in the outermost frame, which magnifies the torsional response due to more unbalanced distribution of stiffness and strength, and causes another failure in inner frames.

Most of Japanese R/C buildings that need seismic retrofit have brittle members. However few investigations concerning the influence of brittle failure on response of asymmetric structures have been made. To investigate the influence of brittle failure on response of asymmetric buildings, torsional response analyses of single-story model structures consisting of brittle and ductile members are carried out, and their results are discussed in this paper.

2. BASIC ASSUMPTIONS

2.1. Model Structures

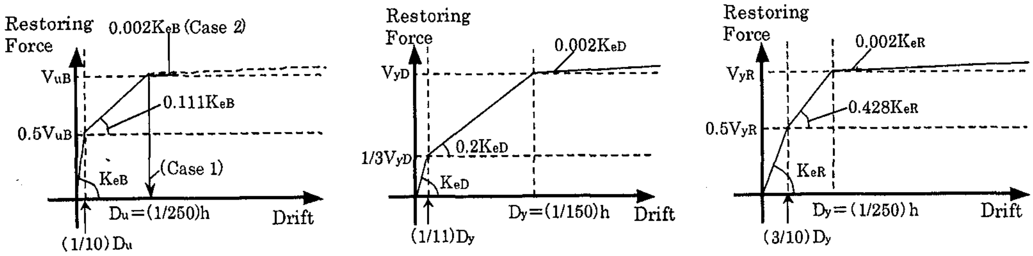
The building investigated in this paper is an idealized single-story structure as shown in **Fig. 2 (A)** consisting of frames and rigid slab with uniformly distributed mass. The longitudinal frames are assumed to consist of existing members and new retrofit members. The equivalent torsional vibration model of the buildings is shown in **Fig. 2 (B)**. Existing members are assumed to consist of brittle members and ductile members. The longitudinal frames parallel to X-axis are modeled with inelastic springs, which represent brittle members, ductile members and retrofit members. The transverse frames parallel to Y-axis are assumed elastic. Torsional stiffness of members is neglected.



(A) Plan of Model Structure **(B) Analytical Model**

Fig. 2 Model structure

Fig. 3 shows the envelope of force-drift relationship of each member. The envelopes are assumed to be the same in both directions of drift. The Origin-Oriented hysteretic model is employed for brittle members and Takeda hysteretic model[2] for both ductile and retrofit members. To investigate the influence of brittle failure on structural responses, two cases are studied in this paper. The first case assumes that brittle members lose their whole strength immediately after reaching their ultimate strength (*Case 1*). The second case assumes that brittle members maintain their strength after reaching their ultimate strength (*Case 2*). Both ductile and retrofit members are assumed to maintain their strength after yielding as shown in **Fig. 3**.



(A) Brittle Member (Column failed by Shear)

(B) Ductile Member (Column failed by Flexure)

(C) Retrofit Member

where h : story height = 3.75m

Fig. 3. Envelopes of force-drift relationship employed in the numerical analyses

2.2. Equation of Motion

The equation of motion for numerical analyses is expressed as follows. Denoting the displacement increment at the center of mass at a certain time step during numerical integrations as $(\Delta x, \Delta y, \Delta\theta)$, the restoring force increment of the longitudinal frame-i parallel to X-axis can be obtained by **Eq. (1)**.

$$\Delta_i V_X = {}_i K_X \cdot (\Delta x + {}_i l_Y \cdot \Delta\theta) \tag{1}$$

Where ${}_iK_X$: instant stiffness of the longitudinal frame-i at a certain time step ($= {}_iK_B + {}_iK_D + {}_iK_R$)
${}_iK_B$: instant stiffness of brittle member at frame-i
${}_iK_D$: instant stiffness of ductile member at frame-i
${}_iK_R$: instant stiffness of retrofit member at frame-i
${}_il_Y$: distance between frame-i and the center of mass

The restoring force increment of the transverse frame-j parallel to Y-axis can be obtained by **Eq. (2)**.

$$\Delta_j V_Y = {}_j K_Y \cdot (\Delta y - {}_j l_X \cdot \Delta\theta) \tag{2}$$

Where ${}_jK_Y$: instant stiffness of the transverse frame-j at a certain time step
${}_jl_X$: distance between frame-j and the center of mass

Let the earthquake ground motion be considered as unidirectional ground motion in X-direction defined by acceleration $\ddot{x}_0$. The equation of motion can be simply expressed by **Eq. (3)** when the viscous damping is neglected.

$$\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix} \cdot \begin{Bmatrix} \Delta\ddot{x} + \Delta\ddot{x}_0 \\ \Delta\ddot{y} \\ \Delta\ddot{\theta} \end{Bmatrix} + \begin{bmatrix} \sum_i {}_iK_X & 0 & \sum_i {}_iK_X \cdot {}_il_Y \\ 0 & \sum_j {}_jK_Y & -\sum_j {}_jK_Y \cdot {}_jl_X \\ \sum_i {}_iK_X \cdot {}_il_Y & -\sum_j {}_jK_Y \cdot {}_jl_X & \sum_i {}_iK_X \cdot {}_il_Y^2 + \sum_j {}_jK_Y \cdot {}_jl_X^2 \end{bmatrix} \cdot \begin{Bmatrix} \Delta x \\ \Delta y \\ \Delta\theta \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \tag{3}$$

Where m, I: mass and moment of inertia of model structure, respectively

The damping matrix is assumed to be proportional to the instant stiffness matrix and is assumed 3 % of critical damping for the first mode in this study. Newmark-β method $(\beta = 1/4)$ is applied in numerical integrations. The time increment for numerical analysis is 0.002 second. The unbalanced force due to the brittle failure and the change of stiffness is corrected at next time step during numerical analyses.

2.3. Parameters for Analytical Models

Fig. 4 shows analytical models investigated in this study, which consist of 3 bays in X-direction and 2 bays in Y-direction, each span length of which are 4.5 m and 6.0 m, respectively. The story height of the model is assumed 3.75m. The weight is assumed to be uniformly distributed across the slab (assumed 11.8kN/m^2 (=1.2tonf/m^2)). The total ultimate strength V_0 of the retrofitted model is 0.75W(75% of the total building weight W) to simulate typical R/C school buildings in Japan retrofitted with R/C walls and/or steel framed braces. The stiffness of the whole buildings in Y-direction, which is elastic in this study, is assumed to be identical with the elastic stiffness of ductile members that yields at 0.45W. The elastic stiffness of transverse frame is assumed to be the same for each frame: the elastic stiffness of transverse frame ${}_jK_Y$ is obtained by **Eq. (4)**.

$${}_jK_Y = \frac{1}{4}\cdot\frac{(1/3)\cdot(0.45W)}{(1/11)\cdot(1/150)\cdot h} \tag{4}$$

To investigate the influence of brittle failure of members on torsional responses, the following parameters are considered: **(1) distribution of retrofit members, (2) strength ratio of brittle members to the total existing members in each frame, (3) hysteretic rule of brittle members.**

(1) Distribution of retrofit members: To investigate the influence of unbalanced distribution of members, three analytical models are studied as shown in **Fig. 4**. Model-A is a symmetric model with respect to X-axis (**Fig. 4 (A)**). Model-B and -C are asymmetric models (**Fig. 4 (B) and (C)**). As shown in **Fig. 4**, new members to retrofit the existing building are installed in Frame-2 and/or Frame-3. Yield strengths of whole members in each model are shown in **Table 1**. All models are symmetric with respect to Y-axis.

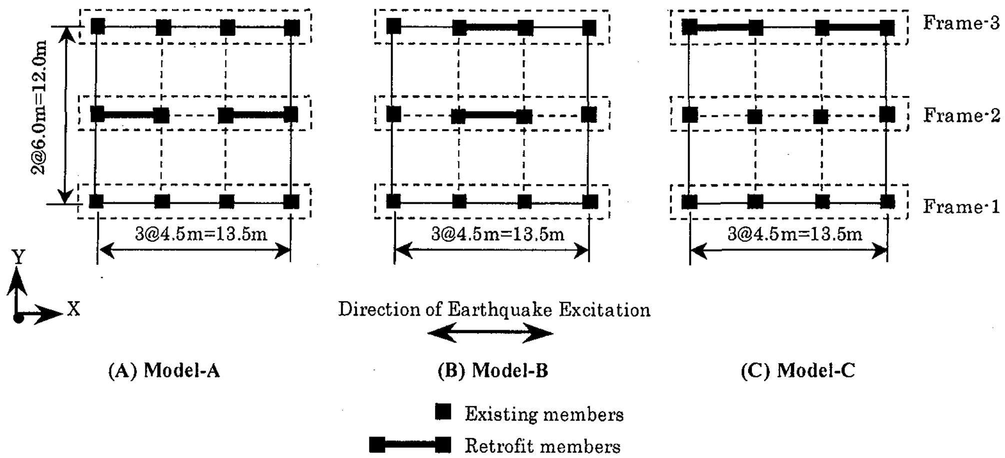


Fig. 4 Analytical Model

Table 1 Ultimate strength of members in analytical model

	Analytical Model	Model - A	Model - B	Model - C
Frame-3	Existing Member ${}_3V_{yBD}$	0.150W	0.075W	0
	Retrofit Member ${}_3V_{yR}$	0	0.225W	0.450W
Frame-2	Existing Member ${}_2V_{yBD}$	0	0.075W	0.150W
	Retrofit Member ${}_2V_{yR}$	0.450W	0.225W	0
Frame-1	Existing Member ${}_1V_{yBD}$	0.150W	0.150W	0.150W

Note: $\sum_{i=1}^{3}\left({}_iV_{yBD}+{}_iV_{yR}\right)=V_0=0.75W,\ \sum_{i=1}^{3}{}_iV_{yBD}=0.30W,\ \sum_{i=2}^{3}{}_iV_{yR}=0.45W$ for all analytical models

(2) Strength ratio of brittle members to the total existing members in each frame: Strength ratio of brittle members to the total existing members, α , is defined as **Eq.(5)**.

$$\alpha=\frac{{}_iV_{uB}}{{}_iV_{yBD}}=\frac{{}_iV_{uB}}{{}_iV_{uB}+{}_iV_{yD}} \qquad (5)$$

Where ${}_iV_{yBD}$: total ultimate strength of existing members in frame-i(= ${}_iV_{yB}+{}_iV_{uD}$)

${}_iV_{uB}$: ultimate strength of brittle members in frame-i

${}_iV_{yD}$: yield strength of ductile members in frame-i

In this study, strength ratio α is assumed to be the same for each frame. Five sets of strength ratio α are considered to investigate the influence of strength ratio α: α =0.1, 0.3, 0.5, 0.7, 0.9. Parameters of those analytical models are shown in **Table 2**.

Table 2 Parameters of analytical model

Strength Ratio of brittle members to the total existing members α		α =0.1	α =0.3	α =0.5	α =0.7	α =0.9
Model - A	E	0.000	0.000	0.000	0.000	0.000
	J	1.131	1.133	1.134	1.136	1.137
	R_E	0.000	0.000	0.000	0.000	0.000
	T_1	0.201	0.191	0.182	0.174	0.167
	T_2	------	------	------	------	------
Model - B	E	0.144	0.106	0.066	0.036	0.009
	J	1.204	1.183	1.167	1.154	1.143
	R_E	0.120	0.090	0.057	0.031	0.008
	T_1	0.206	0.193	0.183	0.174	0.167
	T_2	0.165	0.160	0.155	0.150	0.146
Model – C	E	0.291	0.209	0.132	0.072	0.020
	J	1.270	1.234	1.199	1.172	1.147
	R_E	0.235	0.172	0.111	0.062	0.012
	T_1	0.214	0.198	0.185	0.175	0.167
	T_2	0.153	0.151	0.150	0.148	0.145

Note $E={e}/{r},\ J={j}/{r},\ R_E={E}/{\sqrt{J^2-E^2}},\ r=\sqrt{{I}/{m}}$

e : elastic eccentricity j : radius of torsional stiffness with respect to the center of mass

r : radius of gyration of the floor

R_E : eccentricity index on Japanese design code

T_1, T_2: natural period (sec.) for the first and second mode, respectively

(3) Hysteretic rule of brittle members: As previously discussed in **2.1**, two hysteretic rules are modeled for brittle members to investigate the influence of brittle failure to torsional responses. The first case assumes to lose their whole strength immediately after reaching their ultimate strength at 1/250 of story height in either positive or negative loading stage (*Case 1*). The second case assumes that the brittle members maintain their strength beyond deformation 1/250 of story height (*Case 2*). The envelopes of force-drift relationship for both cases are shown in **Fig. 3(A)**.

2.3. Input Ground Motion

Two ground motions are used in this study: the NS component of the Tohoku University record obtained during the 1978 Miyagiken-oki earthquake (referred to as TOH) and the NS component of the El Centro record obtained during the 1940 Imperial Valley earthquake (referred to as ELC). The first 25 seconds of both records are used in this study. Their peak values are scaled to 0.4g(=3.92 m/s^2) to obtain the maximum drift of a symmetric brittle structure model with ultimate strength 0.75W to 1/250 of story height. The absolute acceleration response spectra with 3% critical damping for both ground motions are shown in **Fig. 5**. **Table 3** shows the original PGA and amplification factor for both ground motions.

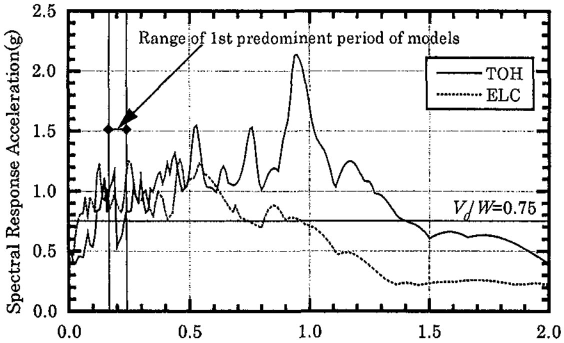


Fig. 5 Acceleration Response Spectra

Table 3 List of Ground Motions

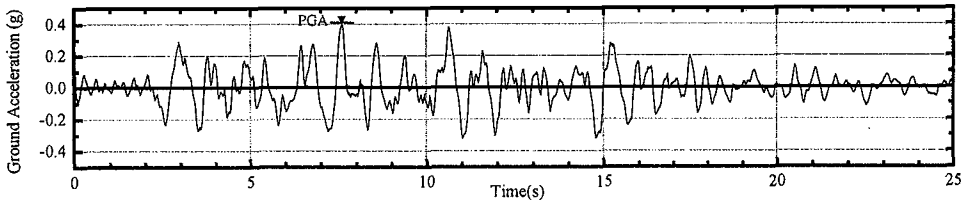
Ground Motion Record Name	Original PGA	Amplification Factor
TOH	0.26g(=2.58m/s^2)	1.538
ELC	0.35g(=3.41m/s^2)	1.143

3. RESPONSE RESULTS

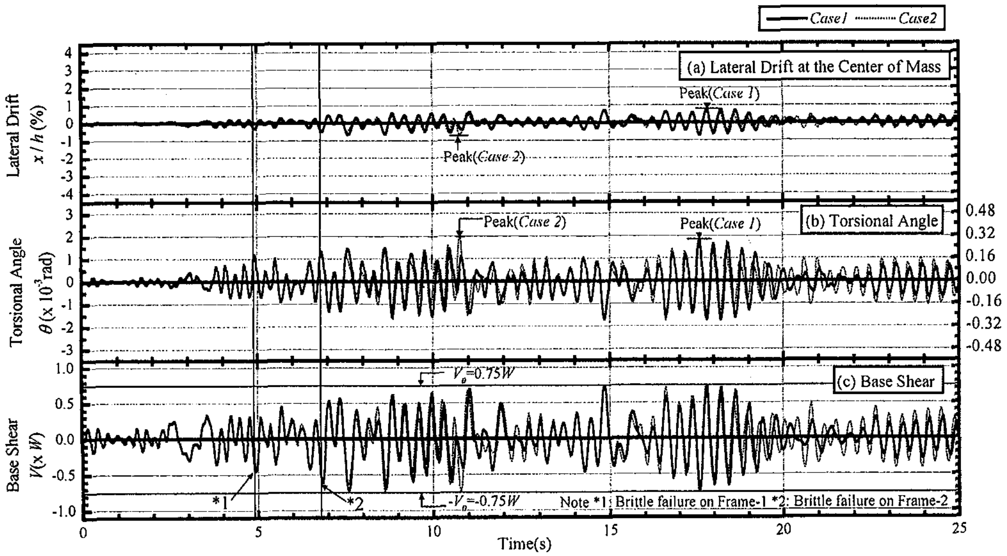
3.1 Influence of Brittle Failure on Response of Asymmetric Models

To investigate the influence of brittle failure on the response of whole structure, the responses of asymmetric models, which have different strength ratio (α = 0.1: ductile and α = 0.9: brittle) and hysteretic rules of brittle members (*Case 1* and *Case 2*), are compared. **Fig. 6** and **Fig. 7** show the time history of ground acceleration, lateral drift x / h at the center of mass, torsional angle θ and base shear V for Model-C subjected to TOH and ELC, respectively. **Fig. 6(B)** and **Fig. 7(B)** show that the response of Model-C with α = 0.1 does not show significant difference in *Case 1* and *Case 2*, while **Fig. 6(C)** and **Fig. 7(C)** show that the response of Model-C with α = 0.9 differs significantly in two cases.

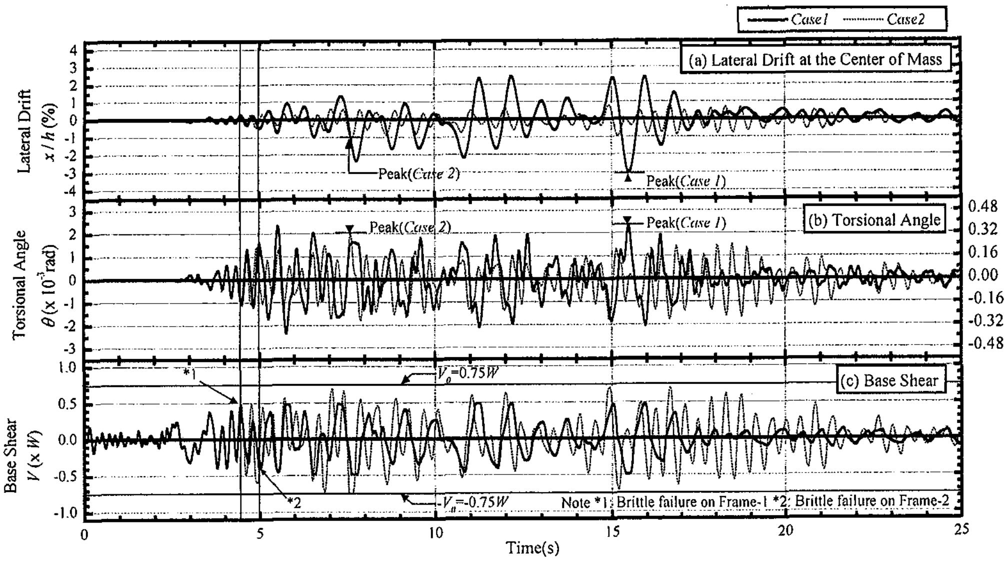
Fig. 6(C)-(a) and **Fig. 6(C)-(b)** show that the lateral drift x/h and the torsional angle θ increase more significantly after brittle failures in *Case 1*, where brittle members are assumed to lose their strength after reaching their ultimate strength, than in *Case 2*. **Fig. 6(C)-(c)** shows that the base shear V after brittle failure is smaller in *Case 1* than in *Case 2*, which results from degradation of lateral resistance shown in *Case 1* and causes larger translational and torsional responses. However, as can be found in comparison of the lateral drift x / h in **Fig. 6(C)-(a)** with the drift of the outermost frame contributed by torsion θ x l / h (l: distance from the center of mass to the outermost frame) shown in **Fig. 6(C)-(b)**), the torsional response does not



(A) Input Ground Motion



(B) Response of Model-C with α = 0.1



(C) Response of Model-C with α = 0.9

Fig.6 Time History of Model-C with $\alpha = 0.9$ Subjected to TOH

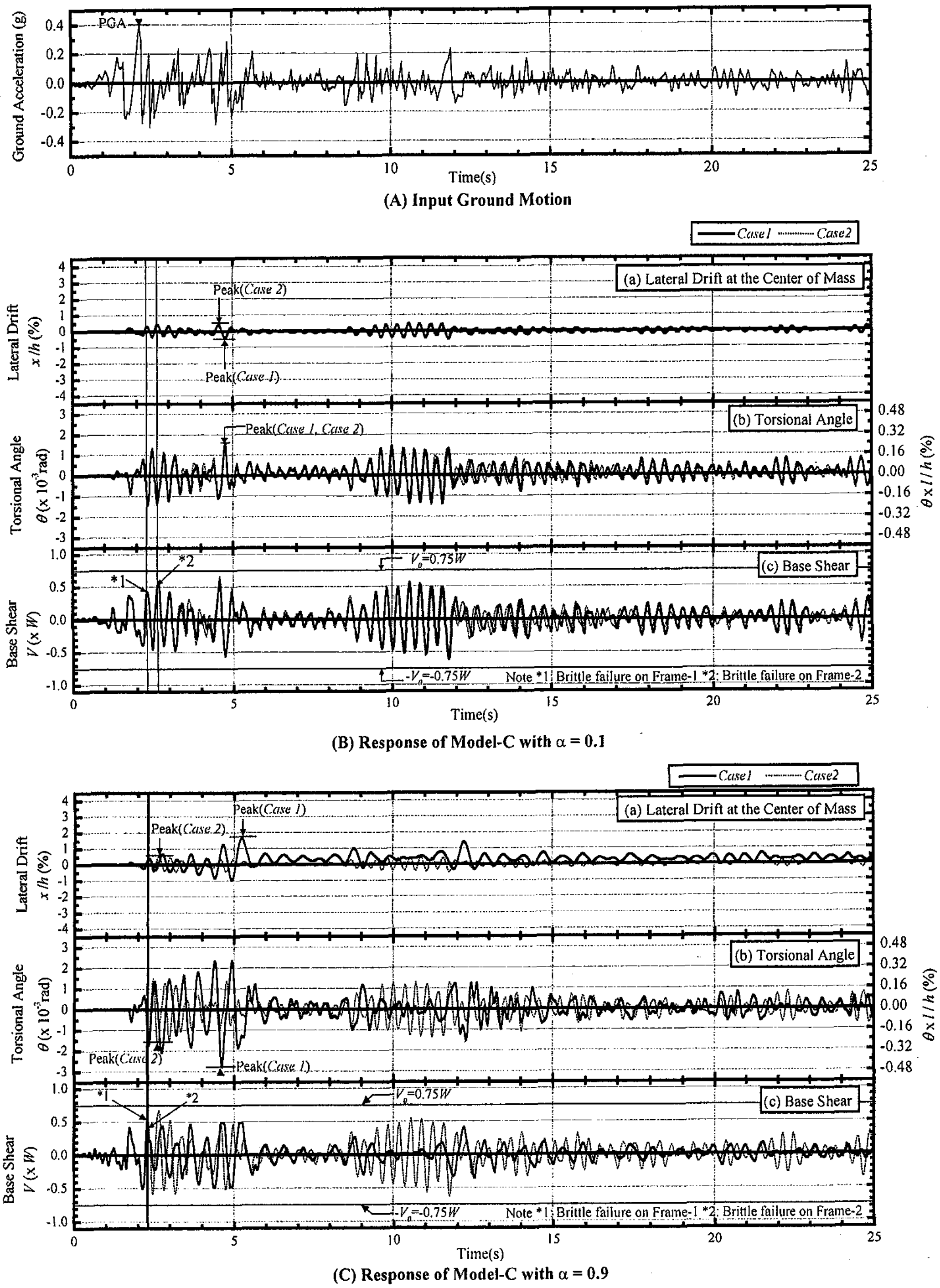


Fig.7 Time History of Model-C with $\alpha = 0.9$ Subjected to ELC

contribute much to the response displacement in the outermost frame in *Case 1*. This is because the lateral drift significantly increases due to decrease in lateral resistance after brittle failure, but the torsional stiffness does not decrease significantly due to the contribution of transverse frames which are assumed elastic in this study and hence the torsional angle increases less significantly. The tendency described above can be also found in **Fig. 7(C)**.

It should be also noted that the response of brittle structures are highly dependent on the ground motion characteristics. As can be found in **Fig. 6(C)**, strong ground motions repeatedly input to the structure even after brittle failure, which magnifies its response. However, **Fig. 7(C)** shows that the structure is subjected to large ground motions within the first 3 seconds; therefore the response is less magnified unlike the results shown in **Fig. 6(C)**.

3.2 Influence of Strength Ratio on Response of Asymmetric Models

Fig. 8 shows the relation of strength ratio α, the maximum lateral drift x_{MAX} / h and the maximum drift of the outermost frame

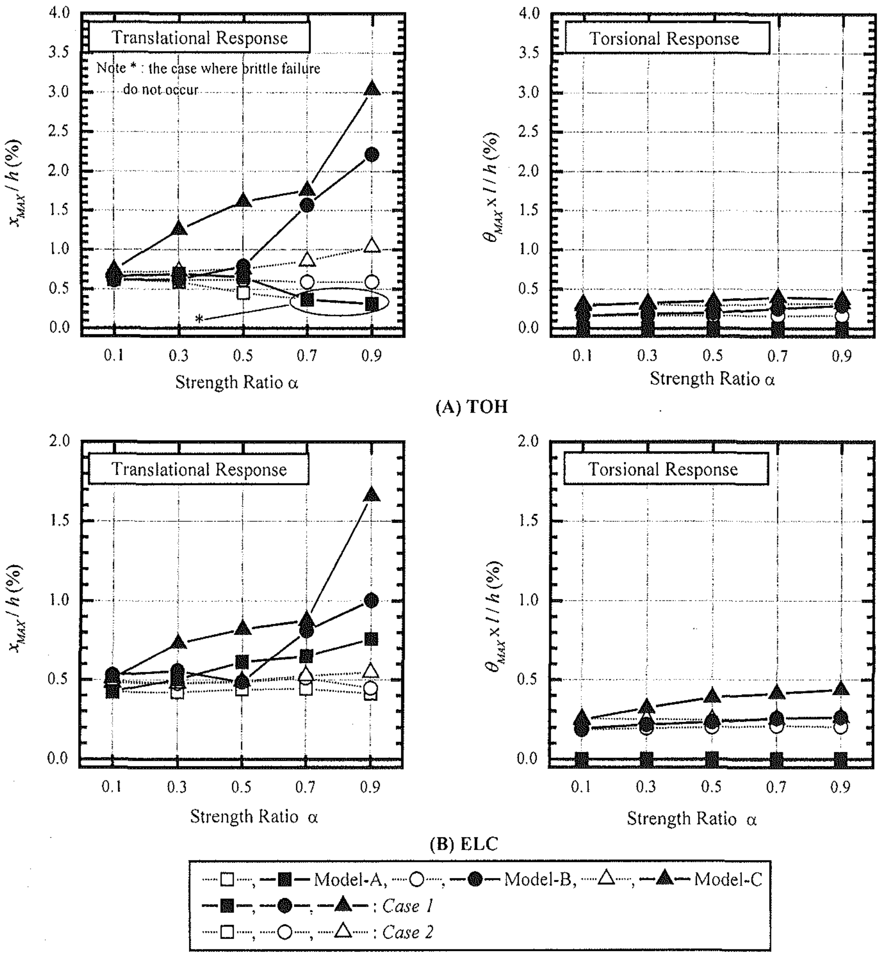
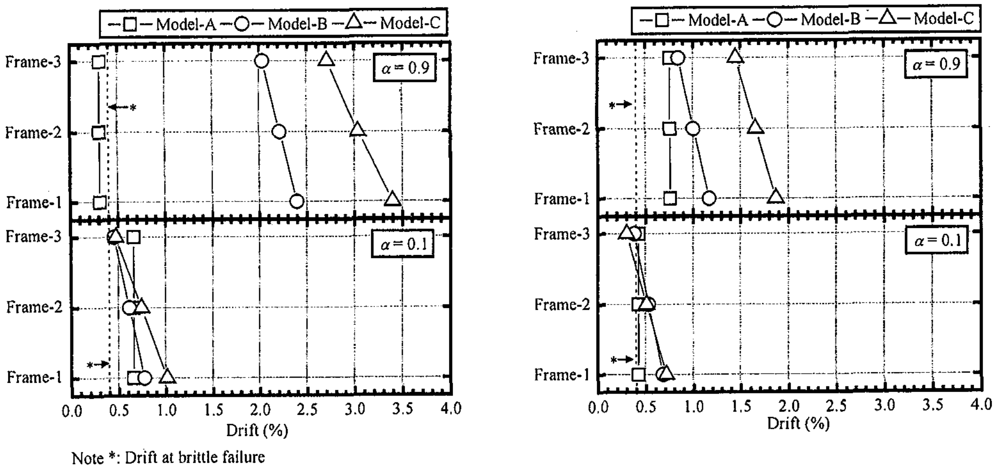


Fig. 8 Relation of strength ratio α, Max. lateral drift x_{MAX} / h and Max. drift of the outermost frame contributed by torsion θ_{MAX} x l / h

contributed by torsion $\theta_{MAX} \times l / h$. This figure shows that x_{MAX} / h of asymmetric models increases significantly with increase in the strength ratio α in *Case 1*, while they are not significantly affected by the strength ratio in *Case 2*. This figure also shows that $\theta_{MAX} \times l / h$ of asymmetric models increase with increase in the strength ratio α in *Case 1*. However $\theta_{MAX} \times l / h$ increases less significantly with increase in α than x_{MAX} / h and the translational displacement mainly governs the response of asymmetric models with larger α in this study.

3.3 Influence of Distribution of Retrofit Members on Response of Brittle Structures

To investigate the influence of the unbalanced distribution of retrofit members on the drift at each frame of brittle and ductile structures, the maximum drift on each frame of structures having different strength ratio ($\alpha = 0.1$: ductile and $\alpha = 0.9$: brittle) are compared. **Fig. 9** shows the maximum drift on each frame of Model-A, B and C in *Case 1*. This figure shows that the drift of all frames of Model-C is remarkably larger than that of Model-B and A when α is 0.9, while it is less different for each model when α is 0.1. This result shows that the distribution of retrofit members affects drift of brittle structure more significantly than that of mainly ductile structures. This may be resulted from the deteriorated lateral resistance due to brittle failures in the outermost frame caused by the torsional response.



(A) TOH **(B) ELC**

Fig. 9 Maximum drift on each frame (*Case 1*)

To investigate the influence of the unbalanced distribution of members on the deterioration of lateral resistance, the base shear V (sum of shear force of each frame) - drift x / h relationship of structures having different distribution of members are compared. **Fig. 10** shows the V - x / h relationship of Model-A, B and C with $\alpha = 0.9$ in *Case 1*. This figure shows that the peak value of V of Model-C is the lowest in the three models and approximately 60% of the total ultimate strength V_0 (=0.75W) that is simply calculated from the sum of each frame's resistance. This is the reason why the Model-C has the largest lateral drift when α is 0.9 as shown in **Fig. 9**.

This result concludes that the response of brittle structures is much more sensitive to the unbalanced distribution of members than that of ductile structures. In seismic retrofit design, engineers therefore should pay more attention to the unbalanced distribution of retrofit members when a building has existing brittle members.

4. CONCLUDING REMARKS

To investigate the influence of brittle failure on response of asymmetric brittle structures, the torsional response analyses of R/C building structure with brittle members are carried out. Although the investigated cases are limited, major findings obtained in this study can be summarized as follows.

(1) The strength degradation of brittle members increases the translational and torsional response of asymmetric structure. However, torsional response increases less significantly than translational response, and hence the translational response governs the response of asymmetric brittle structure in this study.

(2) The lateral resistance of asymmetric brittle structures deteriorates significantly than that of symmetric brittle structures, which magnifies the lateral drift of asymmetric brittle structures more significant than symmetric brittle structures.

(3) The response of brittle structures is much more sensitive to the unbalanced distribution of members than that of ductile structures.

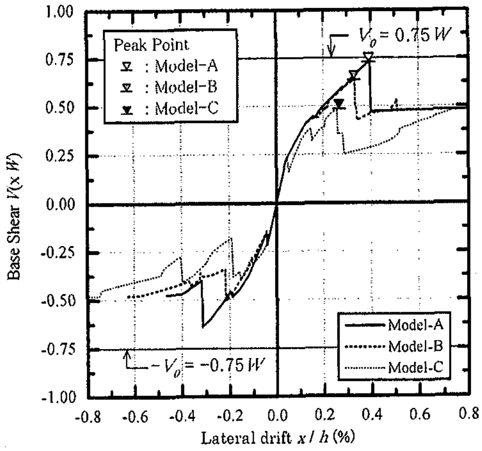


Fig. 10 Relationship between the lateral drift x/h and the base shear V ($\alpha = 0.9$)

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