MULTISTORY BRACING SYSTEMS OF REINFORCED CONCRETE- AND STEEL-RIGID FRAMES SUBJECTED TO HORIZONTAL LOADS
- PROPOSITION OF TOTAL EVALUATION ON THE ASEISMIC CAPACITY FOR DESIGN -

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SUMMARY

Researches on the deformation and fracture characteristics of multistory resisting systems, such as shear walls for reinforced concrete- and bracings for steel-multistory frames, against earthquakes are carried out by the same 1/10 scale models with 3 spans and 3, 6 and 9 stories by the same loading system experimentally as well as analytically. The deformation and fracture behaviours of these multistory frames are totally compared and the differences between their resisting characteristics are clarified by the normalization through the proposed horizontal resisting ratios. Through this comparison the evaluation factors of seismic resistance capacities between these different building systems are presented.

INTRODUCTION

In order to make clear the resisting mechanismus and fracture processes of multistory reinforced concrete shear walls of single core or coupled core types for reinforced concrete structures and of multistory steel bracings for steel structures, tests are carried out on both structural systems by an idealized and simplified loading system. It is intended to propose an evaluation method for the aseismic capacity of these different structural systems and to make possible to compare these capacities not only qualitatively but also quantitatively.

MULTISTORY RESISTING SYSTEMS FOR EARTHQUAKE EXCITATION

Resisting systems of multistory reinforced concrete frames are usually composed of multistory reinforced concrete shear walls by their bending resistance for taller structures and by shearing resistance for lower structures as single center core type or coupled shear wall type shown in Fig.1.

For multistory steel frames there are usually applied multistory bracings of X-truss or K-truss type shown in Fig.1.

TESTING SYSTEM

In order to simulate the earthquake excitation for such multistory frames a concentrated horizontal force V is loaded at the 2/3 level of total height

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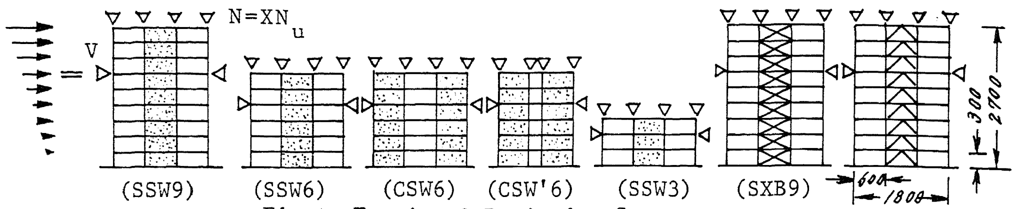


Fig.1 Testing & Resisting Systems

instead of a triangular distribution for each floor levels, which is similar to the distribution of earthquake excitation, for simplicity (see Fig.1). Vertical forces N are loaded simultaneously at the top of each columns with a constant axial load level ratios X (= 0 or 1/3) to the ultimate (or yield) load N_u (or N_y) of all columns.

TESTS

Multistory reinforced concrete shear walls

Tests are carried out on such multistory reinforced concrete frame-shear-wall systems as shown in Fig.1. Test series are consisted of 3-span reinforced concrete frames with 3, 6 and 9 stories. Coupled shear walls and the influences of wall thicknesses are tested on standard 6 story type specimens.

The relationships between horizontal force ratio V_1- horizontal displacement angle R are shown in Fig.2a. Deformations of frames at the ultimate states are illustrated in Fig.3a. Cracking patterns and final fracture modes are illustrated in Fig.4a.

Deformation behaviours and fracture modes of multistory reinforced concrete frame-shear wall systems are classified into two types, i.e. bending type of taller shear walls and shearing type of lower or thinner shear walls.

Bending cracks are formed at the both ends of connecting beams to shear walls at an angle of about R = 0,001. Then tensile cracks by bending are formed at the heel of shear wall in taller bending type and shear cracks are formed from bottom panel of shear wall and spread to the upper stories in lower shear type.

Yield hinges by bending at the both ends of connecting beams to shear walls in each stories and one large yield hinge at the bottom of shear wall with a center of rotation near the compre-sion edge-column of shear wall are formed. General yielding of such reinforced concrete frame-shear wall systems are occurred at an angle of about R = 0,002 $\sim$ 0,003.

Shortly before the final fracture, tenslie cracks are formed at the top of the outside columns in the bottom story of the center core types.
Final fractures are occurred by the shear compression failure of bottom panel in shear walls penetrating into the 1/3 of story heights at an angle of about R = 0,020 for taller bending type but an angle of about R = 0,010 for lower shearing type.

In the cases of thinner shear walls, shear cracks are formed from bottom panel and spread to upper panels at R = 0,001 simultaneously bending tensile cracks are formed in the both ends of each connecting beams. Bending tensile cracks are formed in the bottom of outside columns at R = 0,002. At an angle of R = 0,004 bending tensile cracks are formed at the bottom of shear wall but not soread into wall panel. Final fracture are occurred by the compression fracture at the bottom of outside columns and shear walls at an angle of about R = 0,013.

In the cases of coupled shear walls, bending tensile cracks are formed at the both heels of shear walls at an angle of about R = 0,0005. General yielding and final fracture are occurred at an angle of about R = 0,001 and R = 0,020 respectively.

Multistory steel bracing systems

Tests are carried out on such multistory steel rigid frame-bracing systems as shown in Fig.1. Bracings have rectangular cross section with a slenderness ratio of $\lambda = 64{,}5$ and with carring ratios of resistance of bracings to frames about 0,85 in elastic and 0,50 in collapse mechanism states. Test series are consisted of 3-span steel rigid frames with x-bracings of 3 and 9 stories. Influences of slenderness ratios of bracings are tested in 3 story specimen.

The relationships between horizontal force ratio V_1- horizontal displacement angle R are shown in Fig.2b. Deformations of frames at the ultimate states are illustrated in Fig.3b. Final fracture modes are illustrated in Fig.4b.

Compression bracings in the 2,3,4 and 5 stories are buckled simultaneously at a displacement angle of about R = 0,004 ~ 0,005 and then bracings in 1 and 2 stories. At the alternate cycle, the opposite bracing members are buckled at the same angle too such as shown in Fig.3b.

After buckling of bracings, resistances are carried and increased by the surrounding frames in elastic state and then tensile bracings become effective with the increase of stiffness at a diaplacement angle of about R = 0,020 and hysteresis loops show slipping. Uniform shear deformations are predominant.

Tensile break off of bracings occur at a displacement angle of about R = 0,100, and then resistances of system decrease.

ANALYSIS

Multistory reinforced concrete shear walls

Analytical researches on the deformation behaviours of reinforced concrete multistory frame-shear wall systems have already been developed at first in elastic and then in elasto-plastic ranges (Ref. 2~5). Cardan (Ref. 3) had presented a differential equation on a shear wall-surrounding frame interaction and in this report this differential equation is transformed into a difference equation. Shear wall-surrounding frame systems are abstracted into a model shown in Fig.5 similar to the model by Cardan.

Elemental deformations are assumed such as shown in Figs. 6,7.

Compatibility equations are:

$$\left.\begin{aligned} \phi_i^R &= \phi_{i-1}^R + \frac{1}{2}\theta_i + \frac{1}{2}\theta_{i-1} \\ \phi_i &= \phi_i^R + \phi_i^S \\ \psi_i^B &= \phi_i^R + \frac{1}{2}\theta_i = \phi_{i+1}^R - \frac{1}{2}\theta_{i+1} \end{aligned}\right\} \quad (1)$$

Equilibrium equations are (see Fig.6):

$$\left.\begin{aligned} V_{0i} &= V_{fi} + V_{wi} \\ M_{wi+1} &= M_{wi} - \frac{1}{2}h_i V_{wi} + M_{bi} - \frac{1}{2}h_{i+1} V_{wi+1} \\ M_{bi} &= M_{bi}^B + M_{bi}^S \end{aligned}\right\} \quad (2)$$

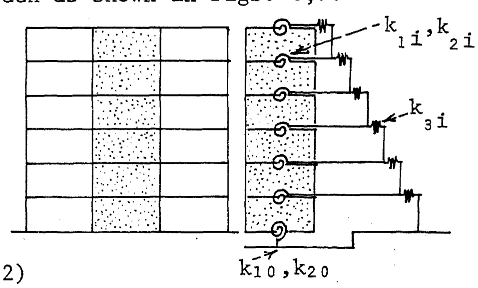


Fig.5 Model for Analysis [3]

Load-deformation relationships of aseismic elements are:

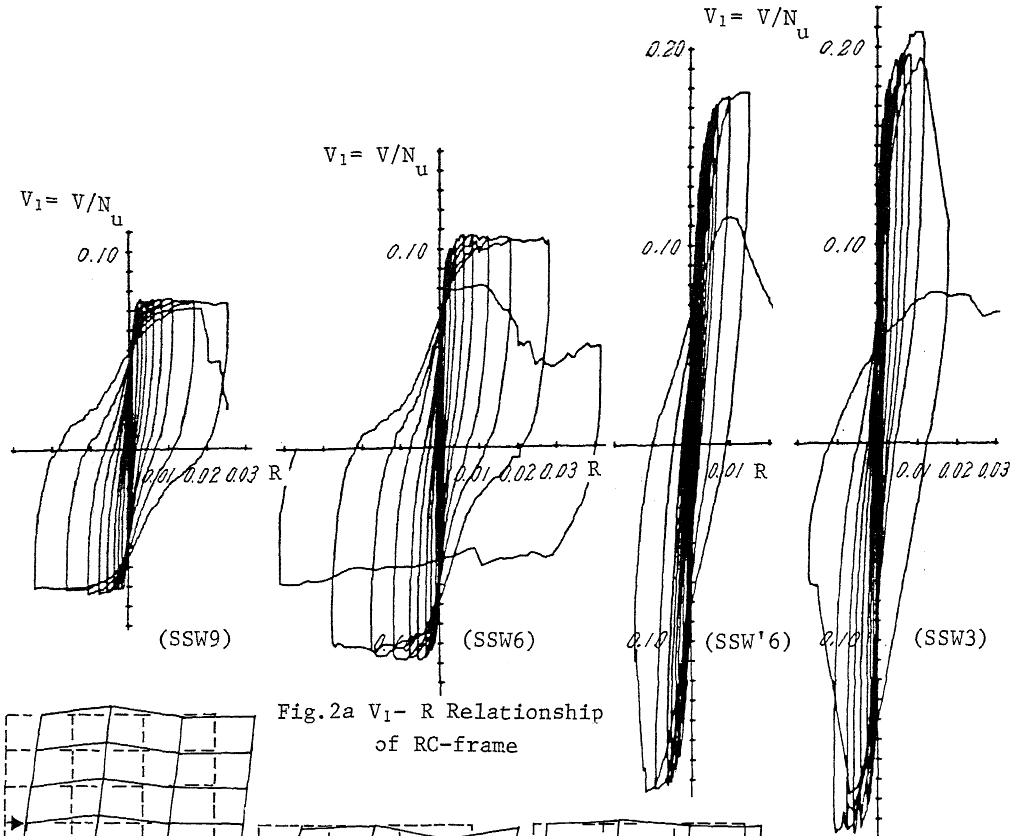


Fig.2a V_1- R Relationship of RC-frame

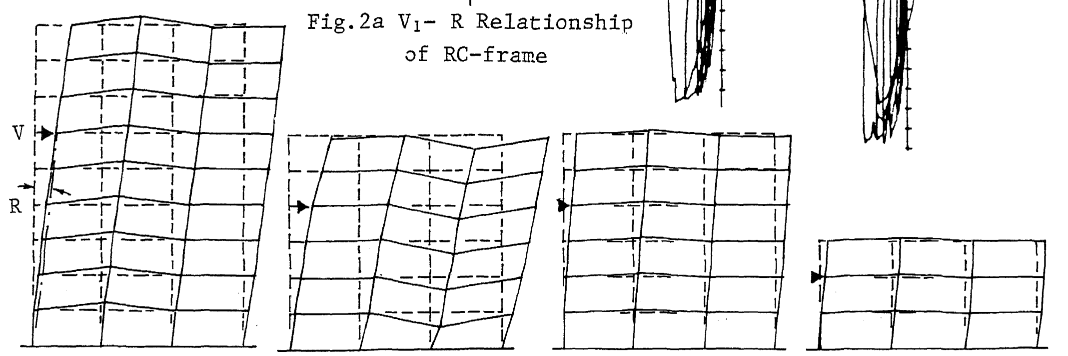


Fig.3a Deformation of RC-frame

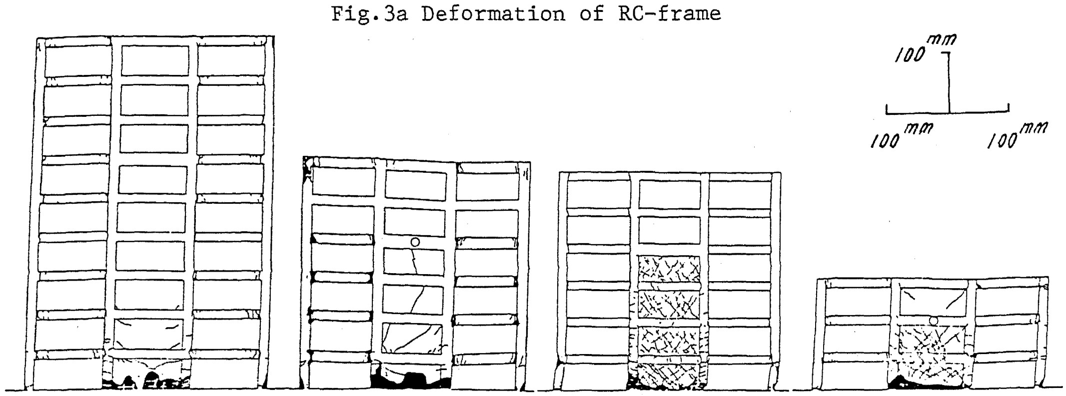


Fig.4a Fracture Mode of RC-frame

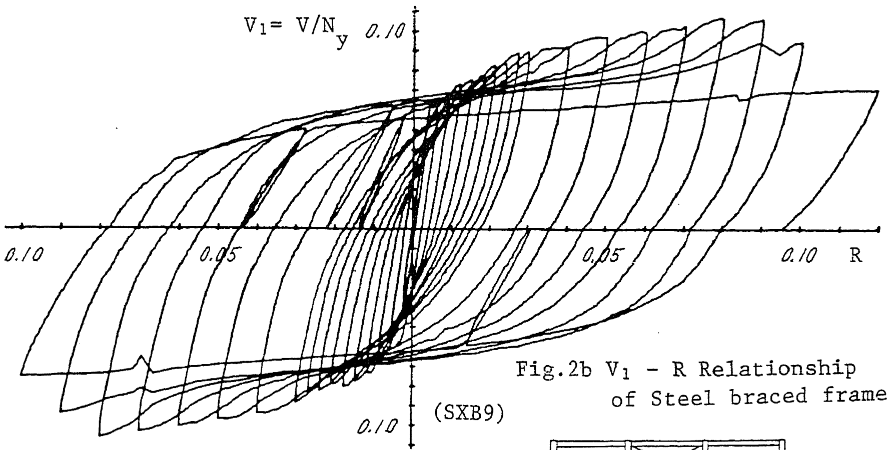


Fig.2b V_1 - R Relationship of Steel braced frame

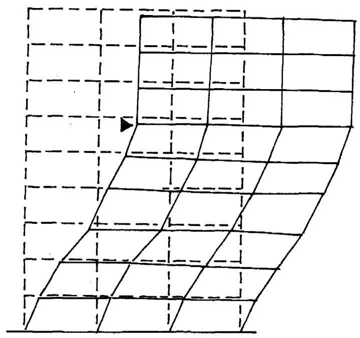


Fig.3b Deformation

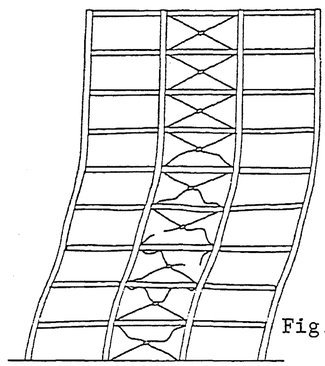


Fig.4b Fracture Mode

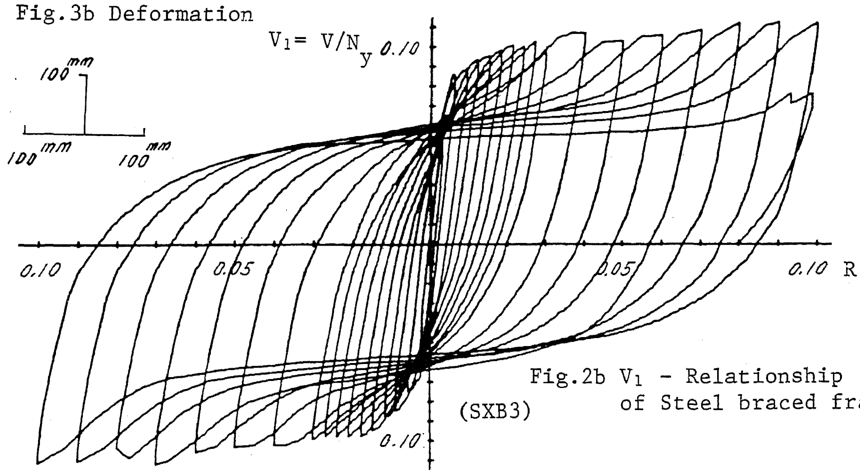


Fig.2b V_1 - Relationship of Steel braced frame

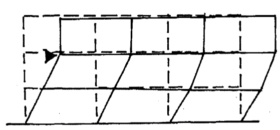


Fig.3b Deformation

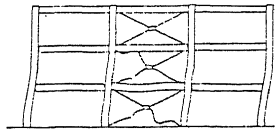


Fig.4b Fracture Mode

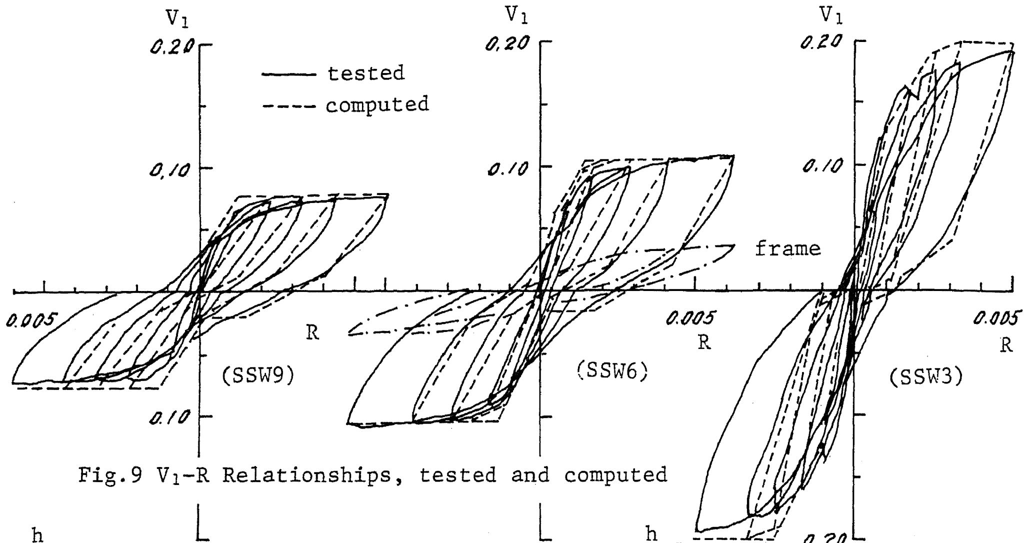


Fig.9 V_1-R Relationships, tested and computed

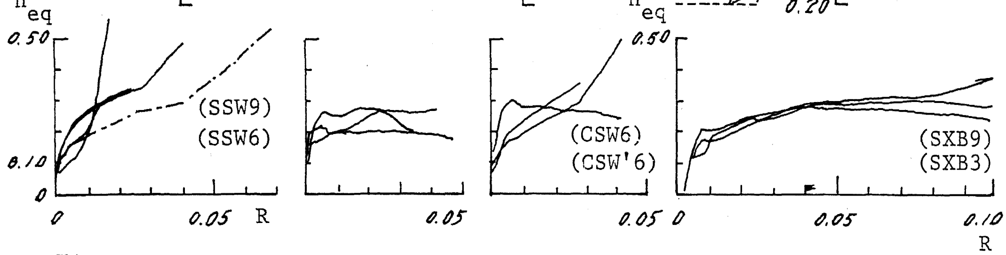


Fig.10 Equivalent damping coefficient h_{eq}

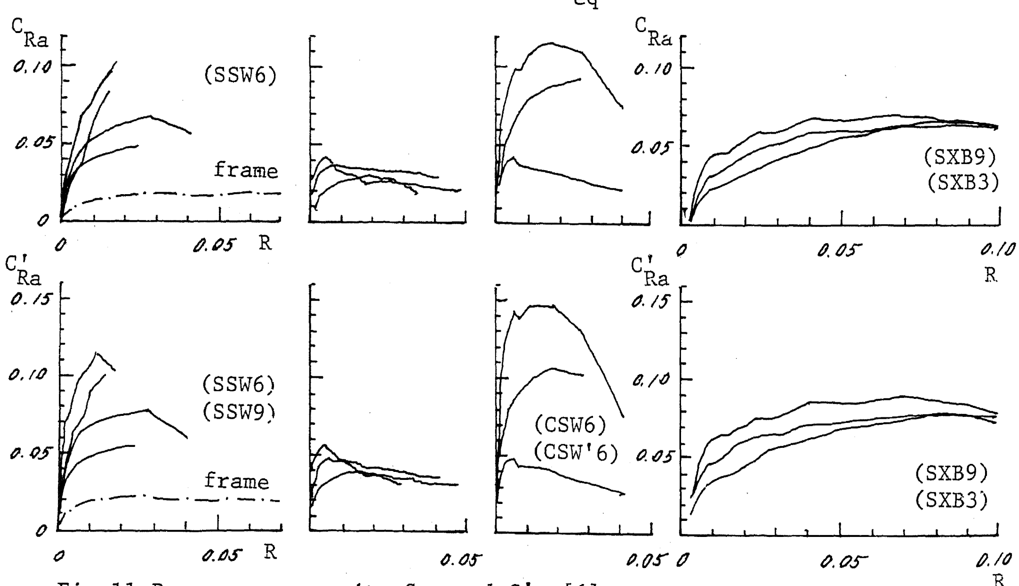


Fig.11 Resonance capacity C_{Ra} and C'_{Ra} [6]

shear walls, bending: $M_{wi} = K^B_i \theta_i$

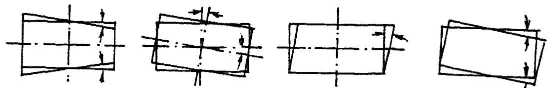
shear: $V_{wi} = K^S_i \phi^S_i$

connecting beams,

bending: $M^B_{bi} = k_{1i}\psi^S_i$

shear: $M^S_{bi} = k_{2i}(\phi^S_i + \phi^S_{i+1})/2$

frames, shear: $V_{fi} = k_{3i}\phi_i$ (3)



bending(θ_i),rocking(ϕ^R_i),shear(ϕ^S_i),rotation(ψ^B_i)

Fig.6 Deformation of Shear Wall

Relationships between external story shear force [V_{0i}] and rotation angle of shear wall [ψ^B_i] are derived as follows:

let eq.(3) into eq.(2),

$$K^B_{i+1}\theta_{i+1} = K^B_i\theta_i - \frac{1}{2}h_i K^S_i \phi^S_i + k_{1i}\psi^B_i + k_{2i}(\phi^S_i + \phi^S_{i+1})/2 - \frac{1}{2}h_{i+1}K^S_{i+1}\phi^S_{i+1} \quad (4)$$

from eq.(3)

$$\psi^B_{i+1} - \psi^B_i = \theta_{i+1}, \quad \psi^B_{i+1} + \psi^B_i = 2\phi^R_{i+1} \quad (5)$$

eq.(3) into eq.(2),

$$\phi^S_i = \frac{V_{0i} - \frac{1}{2}k_{3i}(\psi^B_i + \psi^B_{i-1})}{k_{3i} + K^S_i} \quad (6)$$

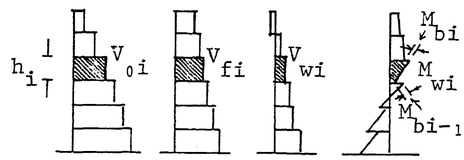


Fig.8 Stress Distribution in Frame

eqs.(5),(6) into eq.(4), then

$$\begin{aligned}
&\left\{K^B_{i+1} + \frac{1}{4}\frac{k_{3i+1}(k_{2i} - h_{i+1}K^S_{i+1})}{k_{3i+1} + K^S_{i+1}}\right\}\psi^B_{i+1} - \left\{(K^B_{i+1} + K^B_i) - \frac{1}{4}\frac{k_{3i+1}(k_{2i} - h_{i+1}K^S_{i+1})}{k_{3i+1} + K^S_{i+1}}\right. \\
&\quad \left. - \frac{1}{4}\frac{k_{3i}(k_{2i} - h_iK^S_i)}{k_{3i} + K^S_i} + k_{1i}\right\}\psi^B_i + \left\{K^B_i + \frac{1}{4}\frac{k_{3i}(k_{2i} - h_iK^S_i)}{k_{3i} + K^S_i}\right\}\psi^B_{i-1} \\
&\quad = \frac{1}{2}\frac{k_{2i} - h_{i+1}K^S_{i+1}}{k_{3i+1} + K^S_{i+1}}V_{0i+1} + \frac{1}{2}\frac{k_{2i} - h_iK^S_i}{k_{3i} + K^S_i}V_{0i} \quad (7)
\end{aligned}$$

Initial conditions are:

for the top floor (i = n)

$$\begin{aligned}
&\left\{K^B_n + k_{1n} - \frac{1}{2}\frac{k_{3n}(k_{2n} - 1/2h_nK^S_n)}{k_{3n} + K^S_n}\right\}\psi^B_n - \left\{K^B_n + \frac{1}{2}\frac{k_{3n}(k_{2n} - 1/2h_nK^S_n)}{k_{3n} + K^S_n}\right\}\psi^B_{n-1} \\
&\quad = -\frac{k_{2n} - 1/2h_nK^S_n}{k_{3n} + K^S_n}V_{0n}
\end{aligned}$$

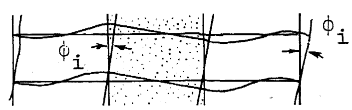


Fig.7 Deformation of i-th. Story

for the bottom floor (i = 0)

(a) fixed ($\psi^B_0 = 0$, $k_{10}, k_{20} = \infty$)

(b) elastic supported ($\psi^B_0 = 0$)

$$\left\{K^B_1 + \frac{1}{2}\frac{k_{31}(k_{20} - 1/2h_1K^S_1)}{k_{31} + K^S_1}\right\}\psi^B_1 - \left\{K^B_1 + k_{10} - \frac{1}{2}\frac{k_{31}(k_{20} - 1/2h_1K^S_1)}{k_{31} + K^S_1}\right\}\psi^B_0 = \frac{k_{20} - 1/2h_1K^S_1}{k_{31} + K^S_1}V_{01}$$

Experimental results shows that reinforced concrete multistory shear wall behaves as a rigid body with a hinge at its bottom especially in bending type such as shown in Fig.4a. Therefore, for numerical analysis here, followings are assumed for simplicity:

(a) shear wall is simplified into a rigid body with a hinge shown in Fig.5,
(b) fundaments are fixed,
(c) k_1 are assumed to be the same value for each story and k_3 are too, except the first story and k_2 are neglected because of $\psi_i^B >> \phi_i^S$.

Computed values are plotted by dotted lines in Fig.9.

COMPARISON AND EVALUATION OF MULTISTORY RESISTING SYSTEMS

Horizontal force ratio V_1

The presenting author (Ref. 1) had proposed for the total evaluation of effects of shear walls or bracings against earthquake excitation, horizontal force ratio V_1, that horizontal resistances of frames (or columns) V are normalized by their ultimate (or yield) vertical resistances N_u (or N_y). In the presented figures these effects are clearly compared quantatively.

Equivalent damping coefficient h_{eq} and resonance capacity C_{Ra}

The authors (Ref. 6) had proposed resonance capacity for the evaluation of aseismic capacity. Here in this paper the resonance capacity is normalized by the ultimate (or yield) vertical resistance too and shown in Figs.10,11.

CONCLUDING REMARKS

Fracture processes and ultimate resistance mechanismus of multistory reinforced concrete frame-shear wall systems and of multistory steel rigid frame-bracing systems are clarified by experiments with the same testing system. Analysis are carried out and compared with test results. Aseismic effects of both construction systems are compared with the same evaluation scale, horizontal resisting ratio V_1 proposed and clarified the differences between their aseismic characteristics not only qualitatively but quantitatively.

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