# SEISMIC RESPONSE OF RC HIGH-RISE BUILDINGS IN JAPAN CONSIDERING INTERNAL VISCOUS DAMPING

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**ABSTRACT :**

Seismic response analyses as an RC high-rise design are in general performed against two different levels of earthquake intensities. Stiffness-proportional damping is chosen for its internal viscous damping. It is customary to use a certain value as a damping ratio in the first mode. On the other hand, recorded values of damping ratios for small earthquake intensity level tend to be smaller than the chosen value for the analysis design of high-rise structures. The variations of seismic response values are evaluated while those analyses are conducted for the various sizes of internal viscous damping. The analysis results show that maximum response values depend on the values of damping constant for the first mode and the differences of damping constant for higher modes. Furthermore, choosing instantaneous stiffness-proportional damping for analysis model, the fluctuating ratios of response values derived from using several cases of damping constant (h1) to those derived from using a damping constant of h1=3% are presented to evaluate the effect of internal viscous damping for earthquake-resistant design. The results show that the response values against large scale intensity motions for h1=2% (instantaneous stiffness-proportional model) are greater among base-shear coefficient, overturning moment, and whole displacement angle by 10% than those for h1=3%. The maximum response values for various values of internal viscous damping are studied for RC high-rise buildings in Japan. Consequently, the effects of internal viscous damping on maximum response values are thoroughly evaluated.

**KEYWORDS:** RC structure, damping, earthquake response analysis, non-linear analysis, high-rise building

## 1. INTRODUCTION

The authors of this paper have been studying the method of earthquake resisting design for high-rise reinforced concrete (RC) buildings with the height of 60 meters and more (Izumi et al., 2006).

The earthquake resisting design of high-rise RC buildings, in general, checks the earthquake resisting safety, and conducts earthquake response analyses that consist of both two earthquake intensity levels (Level1 and Level2); Level1 represents the input motions of rarely occurring earthquakes, and Leve2 represents the ones of very rarely occurring earthquakes (Ministry of Land, Infrastructure, Transport and Tourism, 2007, Japan). The earthquake response analyses of high-rise RC buildings are usually performed on non-linear multi-degree freedom systems subjected to several input earthquake motions. When performing the analyses, the stiffness-proportional damping is chosen for the internal viscous damping. It is quite common for RC structure to use approximately 3% as a design usage for the damping ratio in the first mode (h1).

For high-rise structures, the observed values of damping ratios subjected to small vibrations tend to be smaller than the design usage values. The observed values of the damping ratios in the first mode are

1% to 5%, while the observed values of the damping ratios in the first mode for the structures with the natural period of 1.5 sec. and more range from 1% to 2%. The examination of observed values indicates that for RC structures, the damping ratios in the higher vibration modes tend to be large as the numbers of mode degree become larger, and that the ratios tend to lie in the middle of the two types of damping, stiffness-proportional and constant damping respectively (Architectural Institute of Japan, 2000).

Except for the case of especial observation systems, it is difficult to evaluate the most of observed values of damping ratios by extracting the damping of just upper structure from the observed values due to the effects of dispersion damping by the boundaries of soil layers. Furthermore, there are few opportunities to obtain the data on observed values of major earthquakes; it seems to be difficult to evaluate the damping ratios of relatively large displacement level from observed values.

On the other hand, it can be understood that the influence of the damping ratios on earthquake response is small due to the fact that the effect of hysteresis damping is relatively large after members are yielded during major earthquakes.

Consequently, for earthquake response, it is important to establish the damping ratios. However, no quantitative grounds on them have been found yet.

Hence, in the case of varying the set-ups of internal viscous damping, it is an essential issue for earthquake resisting design to grasp what kind of difference occurs and the fluctuating range of response values while comparing with the response results by using the damping ratio as the deign usage.

In the paper, the ratios of viscous damping energies and the fluctuation of maximum response values are evaluated while the sizes of damping are varied from the two viewpoints of internal viscous damping: one is the damping ratio in the first mode; the other is the selection of damping method. Furthermore, the main type for internal viscous damping in this study is the instantaneous stiffness proportional damping that is commonly used for high-rise RC structures, and 3% is chosen as the damping ratio in the first mode.

## 2. ANALYSIS PLAN

### *2.1. Structures for Analysis Study*

The analysis studies are performed on five different structures (Izumi et al., 2006) with stories between 20 and 54 stories that cover almost all numbers of floors for existing high-rise RC condominiums in Japan (Table 1). The structural properties of five buildings are established from the examples of high-rise RC condominiums to satisfy the current earthquake resisting codes (Ministry of Land, Infrastructure, Transport and Tourism, 2007, Japan).

### *2.2. Analysis Method*

In order to study the difference of earthquake responses by varied damping ratios, Case A that varies the damping ratios in the first mode, Case B that varies the selection of damping methods, and Case C that varies the damping ratios for Rayleigh damping are established.

In Case A, the damping ratios in the first mode are varied from 1% to 5% that are referred to observed results of damping ratios (Architectural Institute of Japan, 2000) including the mainly used 3%. The instantaneous stiffness proportional damping is used as the internal viscous damping.

In Case B, besides the stiffness proportional damping, the Rayleigh damping method is also used for the damping type because the tendency shows that the observed values in higher degree modes (Takeda et al., 1970) as mentioned above are smaller than the values from the stiffness proportional damping. The stiffness proportional damping types consist of the initial stiffness proportional and instantaneous stiffness proportional. The instantaneous stiffness proportional type evaluates the internal viscous damping that is applied to degrading rigidity due to crack and yielding smaller than the initial stiffness proportional type. In addition, the mainly used 3% is used for the damping ratio in the first mode as the stiffness proportional type. On the other hand, 3% is used for the damping ratio in the first and second modes respectively as the Rayleigh damping.

In Case C, using the method of Rayleigh damping, the damping ratios (h1=h2) are varied from 1% to 5%.

### *2.3. Analysis Model*

Equivalent flexural-shear MDF system which is commonly used for basic dynamic model of earthquake resisting design is chosen as an analysis model. This model consists of equivalent bending and shear springs (bending spring: elastic, shear spring: inelastic) that appropriately express the results from the non-linear static analyses of frames. The restoring force characteristics of shear spring are the Takeda model (Takeda et al., 1970) (Figure 1). In addition, the boundary condition of its base is fixed.

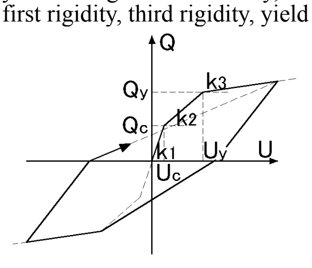
### *2.4. Input Earthquake Motion*

Input earthquake motions are simulated earthquake ground motions with different phases that are based on 2001 Ministry of Construction, Japan, Bulletin #1461 (Table 2). The levels of input earthquake motions consist of Level 1(L1 earthquake motion) and Level 2 (L2 earthquake motion) respectively. Figure 2 shows the pseudo velocity response spectrum of each motion at the bottom of foundation. In addition, the #2 subsurface layer (Shimomaruko area, Tokyo) is assumed as the soil type.

Table 1 Properties of high-rise RC structure

| Case | U20 | R28 | T36 | S45 | S54 |
|---|---|---|---|---|---|
| Storey | 20 | 28 | 36 | 45 | 54 |
| Height (m) | 61.75 | 94.03 | 114.60 | 146.05 | 174.20 |
| dCb | 0.125 | 0.095 | 0.075 | 0.063 | 0.055 |
| $T_1$ (sec.) | 1.32 | 1.99 | 2.27 | 3.05 | 3.49 |
| $Qc/\Sigma W$ | 0.055 | 0.044 | 0.033 | 0.025 | 0.026 |
| $Qy/\Sigma W$ | 0.248 | 0.178 | 0.145 | 0.104 | 0.098 |
| $k_y/k_1$ | 0.266 | 0.272 | 0.323 | 0.335 | 0.302 |
| $k_3/k_1$ | 0.012 | 0.012 | 0.021 | 0.025 | 0.015 |

* Cb: Base shear coefficient of allowable stress design, T1:Natural period in the 1st mode, Qc,Qy: Crack strength, yield strength of 1st storey, ΣW: Total weight, $k_1$,$k_3$,$k_y$: first rigidity, third rigidity, yield point rigidity




TAKEDA Model
(γ=0.4)

Qc : Crack strength
Qy : Yield point strength
Uc : Disp. of crack point
Uy : Disp. of yield point

Table 2 Input seismic wave

| Wave | Level 1 | | Level 2 | | duration time |
|---|---|---|---|---|---|
| | Max. Acc. | Max. Vel. | Max. Acc. | Max. Vel. | |
| | $cm/s^2$ | cm/s | $cm/s^2$ | cm/s | sec. |
| CODE-EL | 89 | 11 | 349 | 55 | 60 |
| CODE-HA | 72 | 14 | 394 | 66 | 80 |
| CODE-BCJ | 76 | 11 | 330 | 54 | 120 |

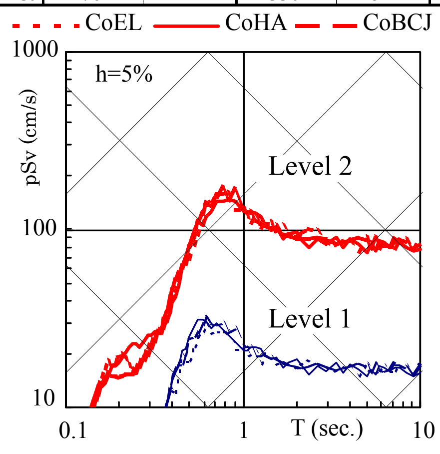


Figure 1 Restoring force characteristics of structure

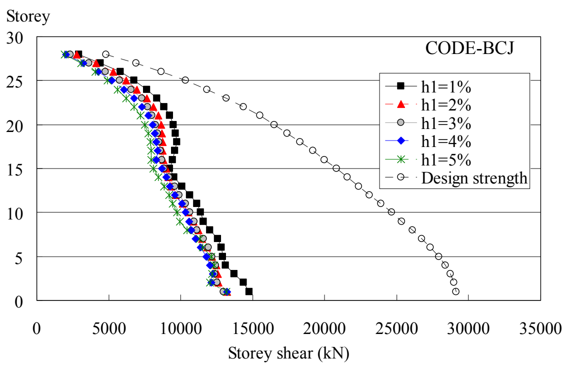
Figure 2 Pseudo-velocity response spectrum

## 3. ANALYSIS RESULTS

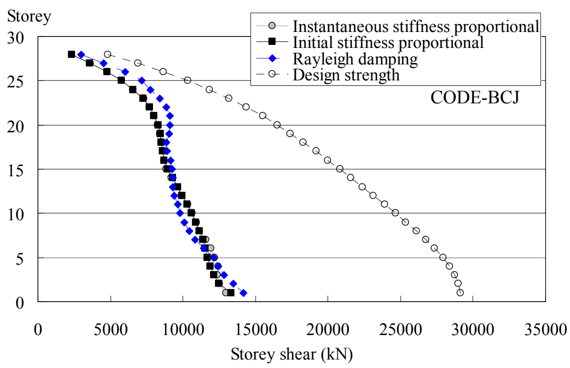
### *3.1. Maximum Response Values*

Figure 3, 4, 5, 6 and 7 show maximum response values for a building, R28 against L1 earthquake vibrations as examples. The response storey shears that are slightly different in stories increase as the values of h1 decrease, while the effect of higher modes on maximum response becomes strong (Figure 3). In upper stories, the storey shears for h1=1% increase by approximately 20% compared to the storey shears for h1=3% while the storey shears for h1=5% decrease by approximately 15%. Also, there is not marked difference in response between the instantaneous stiffness proportional damping and the initial stiffness proportional damping. However, for Rayleigh damping, the effect of higher modes on response can be seen in upper and lower stories. In upper stories, the storey shears for Rayleigh damping increase by approximately 15% compared to the storey shears for the instantaneous stiffness proportional damping. In Figure 3, the response values are much smaller than the storey shears for allowable stress design. This is because larger scale earthquake waves such as standard earthquake vibrations (observed earthquake vibrations of which maximum velocities are amplified) than code waves are used as L1 earthquake vibrations for earthquake resisting design of high-rise buildings; meanwhile, the successiveness in existing design process has been taken into consideration for those larger scale earthquake waves together with code waves. The effect of higher modes on maximum storey angles against L1 earthquake vibrations is more obvious than the one on maximum storey shears (Figure 4). In upper stories, the storey angles for h1=1% increase by approximately 55% compared to the storey angles for h1=3% while the storey angles for h1=5% decrease by approximately 15%. Furthermore, in upper stories, for Rayleigh damping, the storey angles increase by approximately 55% compared to the storey angles for instantaneous stiffness proportional damping.

The storey angles against L2 earthquake vibrations increase as the values of h1 decrease. The storey angles for h1=1% increase by approximately 30% compared to the storey angles for h1=3% while the storey angles for h1=5% decrease by approximately 25% (Figure 5). Also, the more marked effect of decreasing damping ratios can be seen compared to L1 earthquake vibrations while the storey angels for instantaneous stiffness proportional damping are larger han those for initial stiffness proportional damping. For Rayleigh damping, the effect of higher modes on response can be seen. In upper stories, storey angles for initial stiffness proportional damping decrease by approximately 25% compared to the storey angles for instantaneous stiffness proportional damping while those for Rayleigh damping increase by approximately 15%. In these figures, the storey angle of 1/100 is shown as a standard allowable angle against L2 earthquake vibrations. Each response values are less than 1/100. However, considering the uncertainty of damping in higher modes, the values of response storey angles should be sufficiently much less in upper stories.

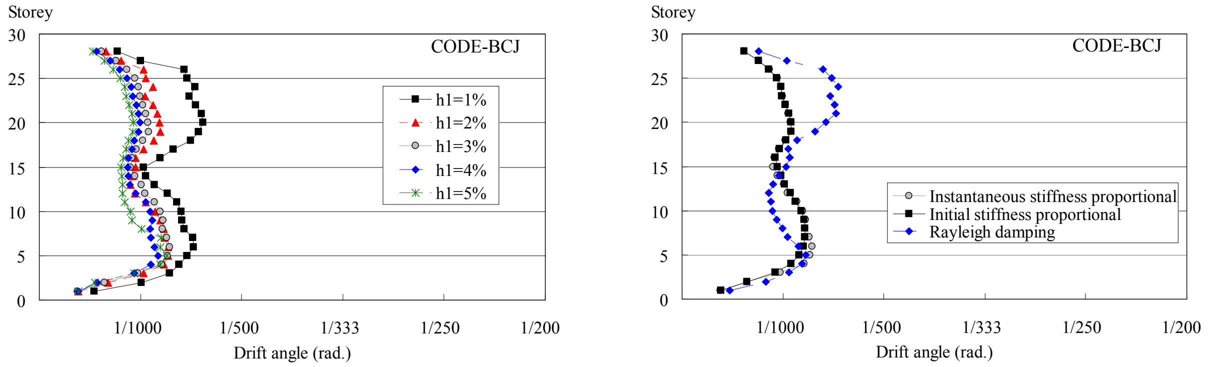



(a) Comparisons of damping ratios (Case A)



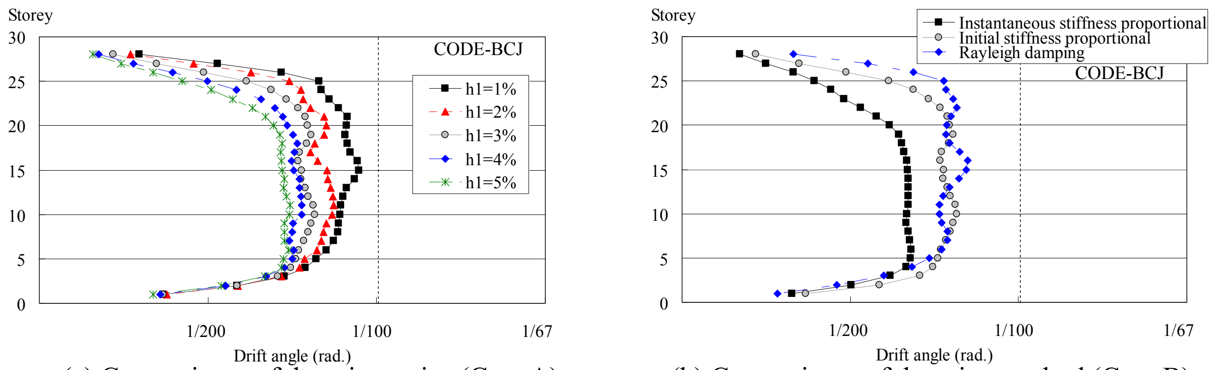

(b) Comparisons of damping method (Case B)

Figure 3 Storey shear of R28 (Level 1)



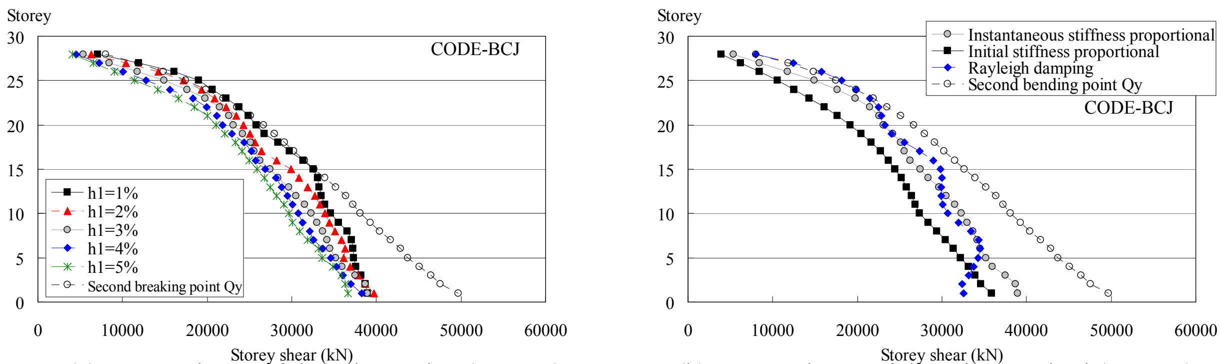

(a) Comparisons of damping ratios (Case A) (b) Comparisons of damping method (Case B)

Figure 4 Drift angle of R28 (Level 1)



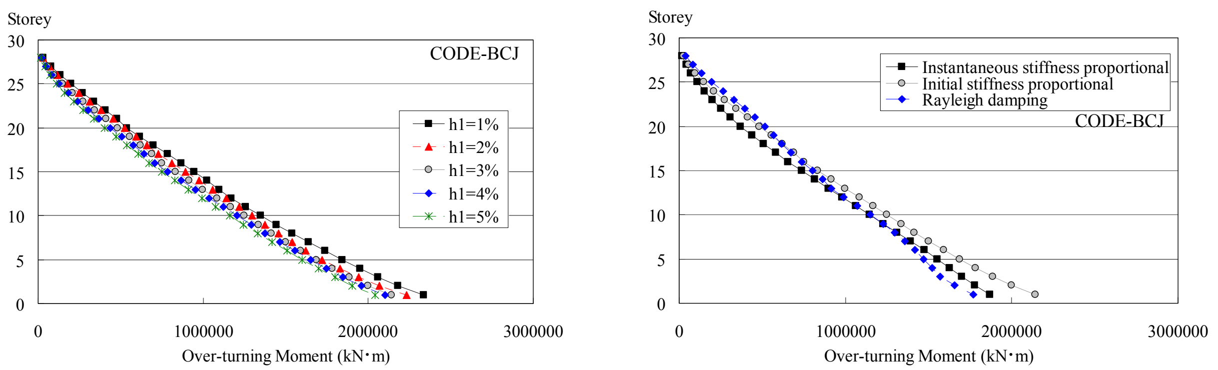

(a) Comparisons of damping ratios (Case A) (b) Comparisons of damping method (Case B)

Figure 5 Drift angle of R28 (Level 2)




(a) Comparisons of damping ratios (Case A) (b) Comparisons of damping method (Case B)

Figure 6 Storey shear of R28 (Level 2)




(a) Comparisons of damping ratios (Case A) (b) Comparisons of damping method (Case B)

Figure 7 Over-turning moment of R28 (Level 2)

In intermediate stories, the storey shears against L2 earthquake vibrations increase as the values of h1 decrease. The maximum values for h1=1% increase by approximately 15% compared to those for h1=3% while the maximum values for h1=5% decrease by approximately 5% (Figure 6). Also, the maximum response storey shears for initial stiffness proportional damping are smaller than those for instantaneous stiffness proportional damping while the maximum storey shears for Rayleigh damping are larger in upper stories and smaller in lower stories. Figure 7 shows that against L2 earthquake vibrations, over-turning moments become more markedly larger as the values of h1 decrease compared to the response values of storey shears. Also, the effect of higher modes on response is notable in Rayleigh damping compared to in stiffness proportional damping.

## 4. DISCUSSION

### *4.1. Difference of Damping Energy Ratios by Varying Damping Ratios and Damping Methods*

Figure 8 shows the comparisons of damping energy ratios for L2 earthquake vibrations by varying damping ratios. The differences of ratios can be slightly seen for each of buildings; meanwhile, no marked tendency is shown for each of natural periods in the first mode. The average values of damping energy ratios for h1=1%, h1=3% and h1=5% are approximately 33%, 55%, and 65% respectively. The average values of damping energy ratios increase as the damping ratios in the first mode increase.

Figure 9 shows the comparisons of damping energy ratios for L2 earthquake vibrations by varying damping methods. The differences of ratios can be slightly seen for each of buildings; meanwhile, no marked tendency is shown for each of natural periods in the first mode as well as the one mentioned above for varying damping ratios. The average values of damping energy ratios for instantaneous stiffness proportional damping, for first stiffness proportional damping and for Rayleigh damping, are approximately 55%, 65% (which is larger), and 46% (which is smaller) respectively.

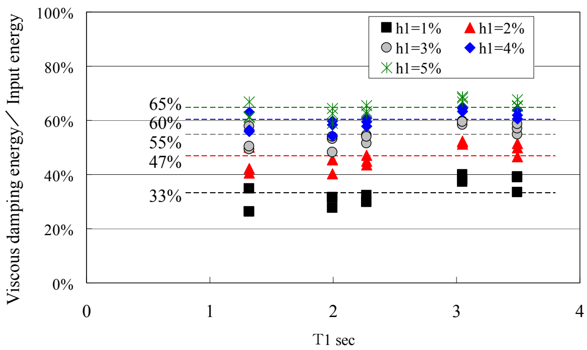



Figure 8 Comparisons of damping energy ratios by varying damping ratios (Case A, Level2)

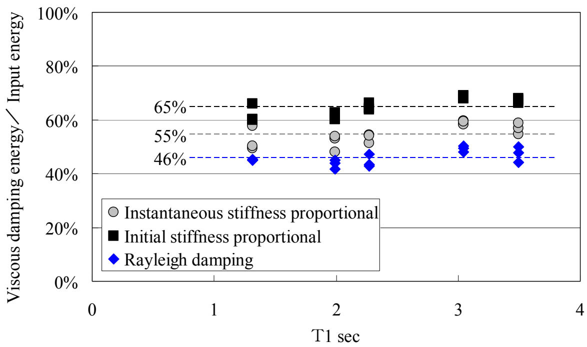



Figure 9 Comparisons of damping energy ratios by varying damping methods (Case B, Level2)

### *4.2. Difference of Maximum Response Values by Varying Damping Ratios and Damping Methods*

The ratios of maximum response values (ratios of response fluctuation) of base shear coefficients (CB), over-turning moments (OTM) and angles of building displacements (TR) are compared to those for basic instantaneous stiffness proportional damping (h1=3%) by varying the damping ratios and damping methods. Here, focusing on the averaged tendency of a response fluctuation extent, the ratios of response fluctuation are the averages of responses from three earthquake waves. Furthermore, the

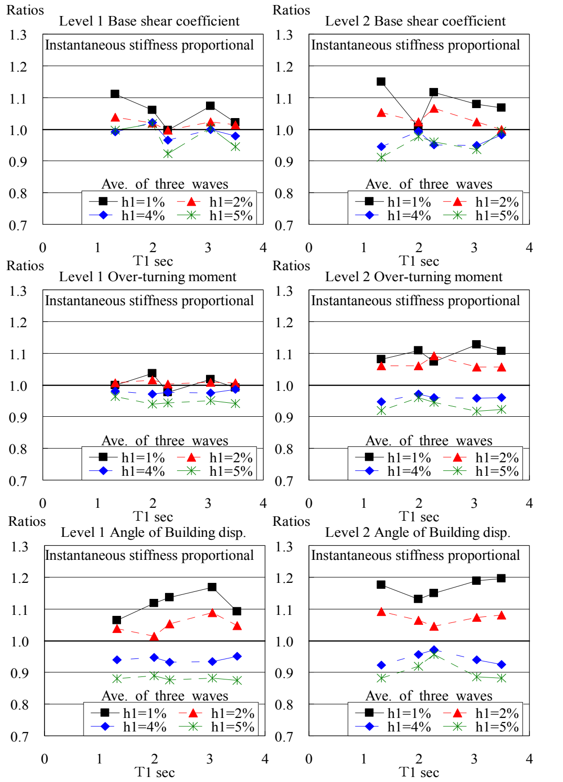



Figure 10 Comparisons of different ratios of response fluctuation by varying damping ratios (Case A)

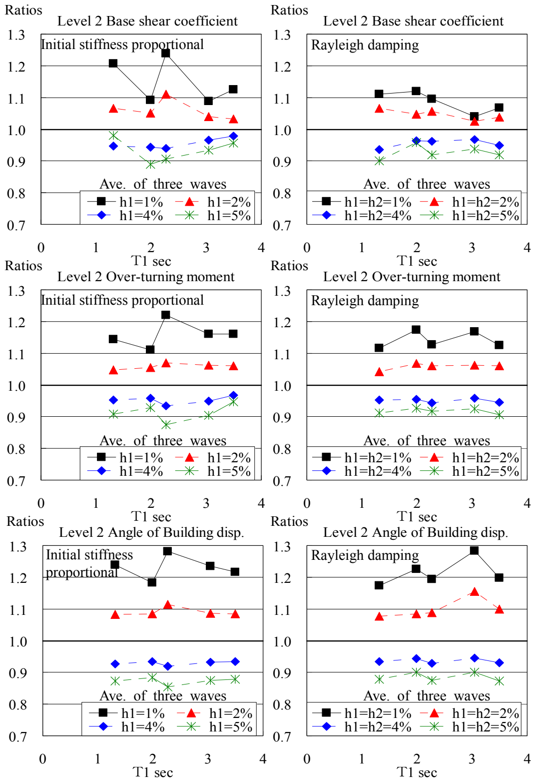



Figure 11 Comparisons of different ratios of response fluctuation by varying damping ratios (Case C)

angle of building displacement is the angle that is obtained from dividing total building displacement at the top by the height of its building.

Figure 10 shows the differences of the ratios of response fluctuation by varying damping ratios in the first mode. Against L1 earthquake vibrations for h1=1%, the ratios of CBs increase by the maximum of 11% compared to those for h1=3% while the ratios of TRs increase by approximately 17%. Against L2 earthquake vibrations, for h1=2%, the all of the ratios of CBs, OTMs, and TRs increase by the maximum of 10%.

Figure 11 shows the differences of the ratios of response fluctuation by varying damping ratios in the first and second modes of Rayleigh damping compared to those for h1=h2=3%. Against L2 earthquake vibrations, for Rayleigh damping, the ratios of CBs, OTMs, and TRs for h1=h2=1% increase by the maximum of 12, 17 and 28% respectively.

Figure 12 shows the differences of the ratios of

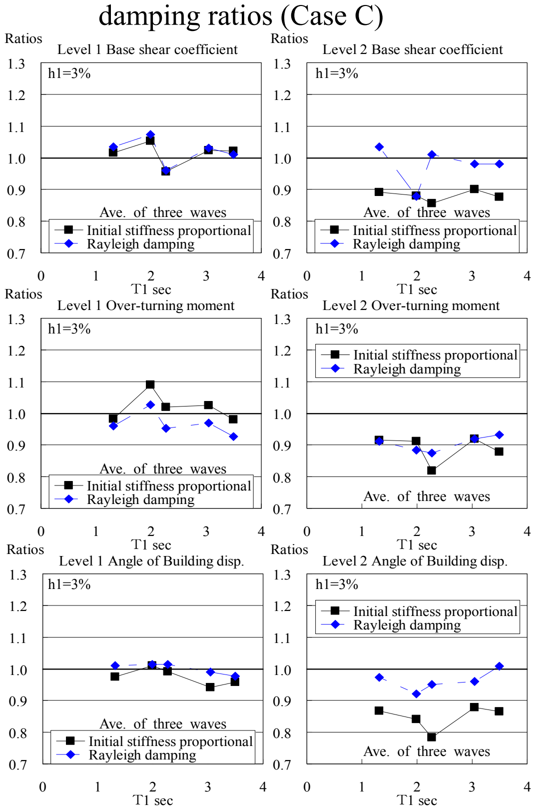



Figure 12 Comparisons of different ratios of response fluctuation by varying damping methods (Case B)

response fluctuation by varying damping methods. For initial stiffness proportional damping, the ratios of response fluctuation against L2 earthquake vibrations are smaller than those against L1 earthquake vibrations. Furthermore, against L2 earthquake vibrations, the ratios of response fluctuations for Rayleigh damping decrease by approximately 10% due to the effect of higher modes on response.

## 5. CONCLUSIONS

The following conclusions were obtained from the earthquake response analyses on high-rise buildings that satisfy the existing earthquake resisting standard in Japan:

(1) For high-rise RC structures, using the commonly used internal viscous damping (instantaneous stiffness-proportional damping, damping ratio in the first mode h1=3%), the averaged ratio of accumulated damping energy to accumulated input energy was approximately 55%.

(2) For various values of the internal viscous damping, the ratios of response fluctuation that demonstrate the response fluctuation extent were presented as for the basic case of design usage damping (instantaneous stiffness-proportional damping, h1=3%).

(3) For the case of h1=2% (instantaneous damping), focusing on the averages of response values, the response values of base shears, overturning moments, and building displacements increase by the maximum of approximately 10%, compared to the response values of the basic case.

(4) For the case of Rayleigh damping (h1=h2=3%), in upper stories, due to the effect of higher modes on response values, the response values of the drift angles increase and the response values of overturning moments decrease, compared to the response values of the basic case.

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