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# The Study on the Behavior under Dynamic and Static Analysis of Reinforced Concrete Core Wall-Perimeter Steel Frame Hybrid Structure, Part II

# RCコア壁付き鉄骨骨組の動的および静的挙動に関する研究（その２）

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We have studied the behavior of Hybrid Structure with reinforced concrete core wall-perimeter steel frame under dynamic and static loads with incremental dynamic analysis (IDA) and static pushover analysis. Three different storey models, 12-storey, 20-storey and 30-storey with diagonally-braced frame have been analyzed. Twenty seismic ground motion records (LA1-LA20, FEMA) can be used to obtain an average response optimally in IDA. We have compared the storey drift angle (SDA) between IDA (ten different intensities, PGV from 10kine to 100kine) and static pushover analysis to estimate more thoroughly structural performance with plastic development; additionally, we have discussed the interstorey shear force amplificatory ratio $\gamma$ between IDA and static pushover analysis, found it's quite related to the input intensity and location along the building. Finally we have discussed the ratio $\alpha$ to obtain the change rule about the ratio $\gamma$ of frame and wall towards the ratio $\gamma$ of total storey.

**Keywords : Reinforced Concrete, Core Wall, Steel Frame, Hybrid Structure, Incremental Dynamics Analysis, Pushover Analysis**
鉄筋コンクリート, 耐震壁, 鉄フレーム, 混合構造, 増分時刻歴応答解析, 荷重増分解析

## 1. Introduction

This paper is the second part of the Study on the behavior under dynamic and static analysis of Reinforced Concrete core wall-Perimeter Steel Frame Hybrid Structure [1)] followed the first part in this report. The first part gave some basic information about this kind of Reinforced Concrete Core Wall-Perimeter Steel Frame Hybrid Structure, the equivalent diagonally-braced frames for reinforced concrete core wall, defined the rules to compare the results between static pushover analysis and time history dynamic analysis. A 6-storey hybrid structure with equivalent diagonally-braced frame was analyzed, the most important result is the interstorey shear force amplificatory ratio $\gamma$ of different intensity between static and dynamic analysis. While discussing the ratio, Incremental Dynamic Analysis (IDA) method was used to find the behavior of the hybrid structure under different levels of seismic intensity. In the paper part I, just a 6-storey model was analyzed, in the paper part II, we will discuss 12-storey, 20-storey and 30-storey models including low-rise, moderate-rise and high-rise buildings which are generally adopted in hybrid structure system in practice. The following paragraph will shown some essential background of Incremental Dynamic Analysis.

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## 2. Incremental Dynamic Analysis

Incremental Dynamic Analysis (IDA) [2,3)] is a parametric analysis method that has recently emerged in several different forms to estimate more thoroughly structural performance under seismic loads. It involves subjecting a structural model to one (or more) ground motion record(s), each scaled to multiple levels of intensity, thus producing one (or more) curve(s) of response parameterized versus intensity level.

The growth in computer processing power has made possible a continuous drive towards increasingly accurate but at the same time more complex analysis methods. Thus the state of the art has progressively moved from elastic static analysis to dynamic elastic, nonlinear static and finally nonlinear dynamic analysis. In the last case the convention has been to run one to several different records, each once, producing one to several analyses, mostly used for checking the designed structure. On the other hand methods like the nonlinear static pushover (SPO) (ATC, 1996) or the capacity spectrum method (ATC, 1996) offer, by suitable scaling of the static force pattern, a "continuous" picture as the complete range of structural behavior is investigated, from elasticity to yielding and finally collapse, thus greatly facilitating our understanding.

By analogy with passing from a single static analysis to the incremental static pushover, one arrives at the extension of a single time-history analysis into an incremental one, where the seismic "loading" is scaled. It has also been adopted by the U.S. Federal Emergency Management Agency (FEMA) guidelines (FEMA, 2000a, b) as the Incremental Dynamic Analysis (IDA) and established as the state-of-the-art method to determine global collapse capacity. The IDA study is now a multi-purpose and widely applicable method and its objectives, include

1. Thorough understanding of the range of response or "demands" versus the range of potential levels of a ground motion record,
2. Better understanding of the structural implications of rarer/more severe ground motion levels,
3. Better understanding of the changes in the nature of the structural response as the intensity of ground motion increases (e.g., change in peak deformation patterns with height, onset of stiffness and strength degradation and their patterns and magnitudes),
4. Producing estimates of the dynamic capacity of the global structural system and
5. Finally, given a multi-record IDA study, how stable (or variable) all these items are from one ground motion record to another.

As a first step, let us define the fundamental concept of scaling an acceleration time history that we need. Assume we are given a single acceleration time-history, selected from a ground motion database which will be referred to as the base, "as-recorded" (although it may have been pre-processed by seismologists, e.g., baseline corrected, filtered and rotated), unscaled accelerogram $\boldsymbol{\alpha}_1$, a vector with elements $\alpha_1(t_i)$, $t_i = t_1, t_2, \ldots, t_n$. To account for more severe or milder ground motions, a simple transformation is introduced by uniformly scaling up or down the amplitudes by a scalar $\lambda \in [0, +\infty)$: $\boldsymbol{\alpha}_\lambda = \lambda \cdot \boldsymbol{\alpha}_1$. Such an operation can also be conveniently thought of as scaling the elastic acceleration spectrum by λ or equivalently. Usually we use Peak Ground Velocity (PGV) to control the input seismic intensity, by using this scaling method we get Table. 1, twenty seismic earthquake records, PGV from 10kine to 100kine.

# 3. Analysis model and method of hybrid structures

## 3. 1 Analytical Method

The floor plan of a representative hybrid building using this structure system is shown in the paper part I [1)]. For simplifying the analysis procedure, we can turn the 3-dimention model into 2-dimention planar model. The pure frame portion and the frame with core walls portion are linked by link elements which have large rigidity with two pin joints that can transfer load and deformation [4)]. Because of the limits of our analysis program, the problem is how to compute the core-wall in our model. In Japan, there is a conventional method to simulate the shear wall with the equivalent diagonally-braced frame mentioned in Masafumi Inoue and Mashide Tomii's paper named Method of estimation of rotational rigidity of the corner connections of framed shear walls for their equivalent diagonally-braced frames [5)], one can see the detail in the paper part I [1)].

## 3. 2 Analytical Model

Three kinds of models were analyzed, 12-storey, 20-storey, 30-storey which include low-rise, moderate-rise and high-rise buildings in practical use. The analytical model is shown in Fig. 2 and 3, the numbers on the

**Table.1** Seismic Record LA1-LA20

| Record | PGV(kine) | STEP(s) | TIME(s) | DATA |
|---|---|---|---|---|
| LA01 | 62.4 | 0.02 | 53.46 | 2674 |
| LA02 | 59.8 | 0.02 | 53.46 | 2674 |
| LA03 | 77.1 | 0.01 | 39.38 | 3939 |
| LA04 | 77.1 | 0.01 | 39.38 | 3939 |
| LA05 | 89.2 | 0.01 | 39.08 | 3909 |
| LA06 | 47.4 | 0.01 | 39.08 | 3909 |
| LA07 | 66.1 | 0.02 | 79.98 | 4000 |
| LA08 | 65.7 | 0.02 | 79.98 | 4000 |
| LA09 | 91.3 | 0.02 | 79.98 | 4000 |
| LA10 | 60.3 | 0.02 | 79.98 | 4000 |
| LA11 | 79.1 | 0.02 | 39.98 | 2000 |
| LA12 | 56.0 | 0.02 | 39.98 | 2000 |
| LA13 | 95.6 | 0.02 | 59.98 | 3000 |
| LA14 | 81.0 | 0.02 | 59.98 | 3000 |
| LA15 | 98.5 | 0.005 | 14.945 | 2990 |
| LA16 | 100.8 | 0.005 | 14.945 | 2990 |
| LA17 | 80.2 | 0.02 | 59.98 | 3000 |
| LA18 | 118.9 | 0.02 | 59.98 | 3000 |
| LA19 | 68.3 | 0.02 | 59.98 | 3000 |
| LA20 | 103.8 | 0.02 | 59.98 | 3000 |

top are the mass for each storey. The average mass is 1.0ton/m$^2$, the story height is 3.6m except 4.0m at the first story, the region coefficient equals to 1.0, the standard base shear coefficient equals to 0.2 at first level and 1.0 at second level. The static pushover load distribution equals to Ai distribution according to the Japanese code (Fig.1) [6]. The seismic waves of the ground motion records for the incremental dynamic time-history analysis are LA1-LA20 (FEMA) (Table. 1). Newmark $\beta$ method is used in the dynamic analysis, the damping factor of the first and the second mode shape equals to 0.03, the factor $\beta$ equals to 0.25. The PGV of the seismic waves from LA01 to LA20 is equal to 10, 20, 30, 40, 50, 60,70, 80, 90, 100kine. The section of each member is shown in Table. 2, 3 and 4, 10% and 5% mean the reinforced bar ratio in concrete sections.

For 12-storey model, the height $H$=43.6m, the first period $T_1$=0.829s, and second period $T_2$=0.222s.

For 20-storey model, the height $H$=72.4m, the first period $T_1$=1.923s, and second period $T_2$=0.449s.

For 30-storey model, the height $H$=108.4m, the first period $T_1$=2.608s, and second period $T_2$=0.648s.

For each model, Time-History dynamic analysis were run 200 times (20 kinds of seismic wave record × 10 kinds of intensity = 200 times analysis).

## 4. Results and Discussion

Our analytical models are three kinds of different height hybrid structures including perimeter steel frame and reinforced concrete core wall, each of them has its own property and deformation pattern. For

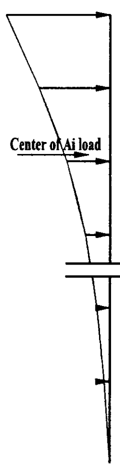



Fig.1 Ai distribition Load

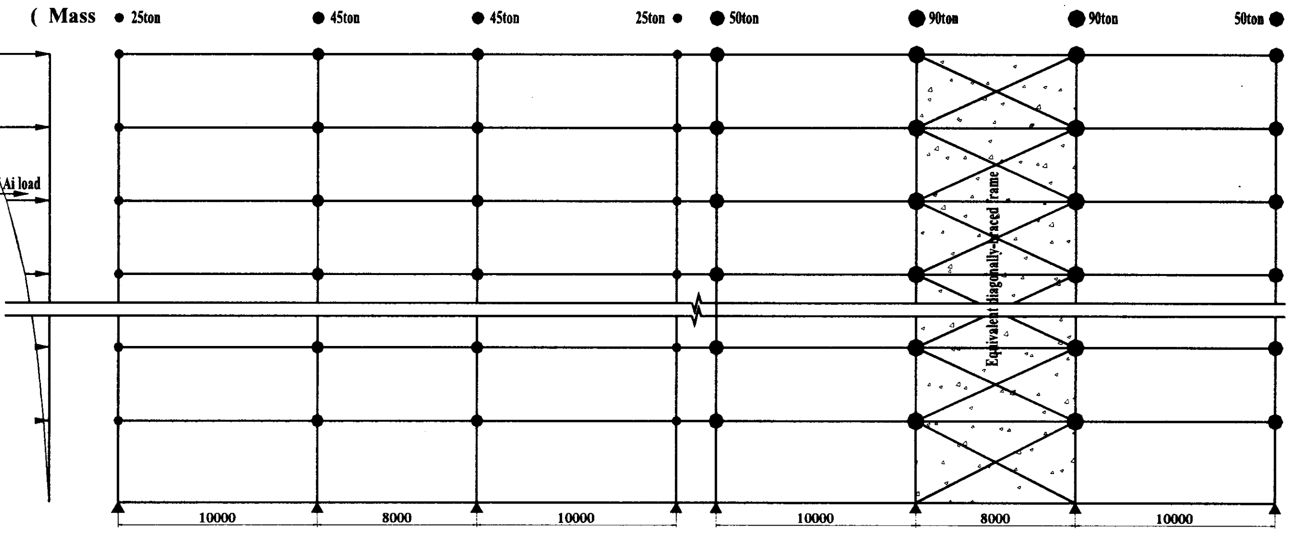
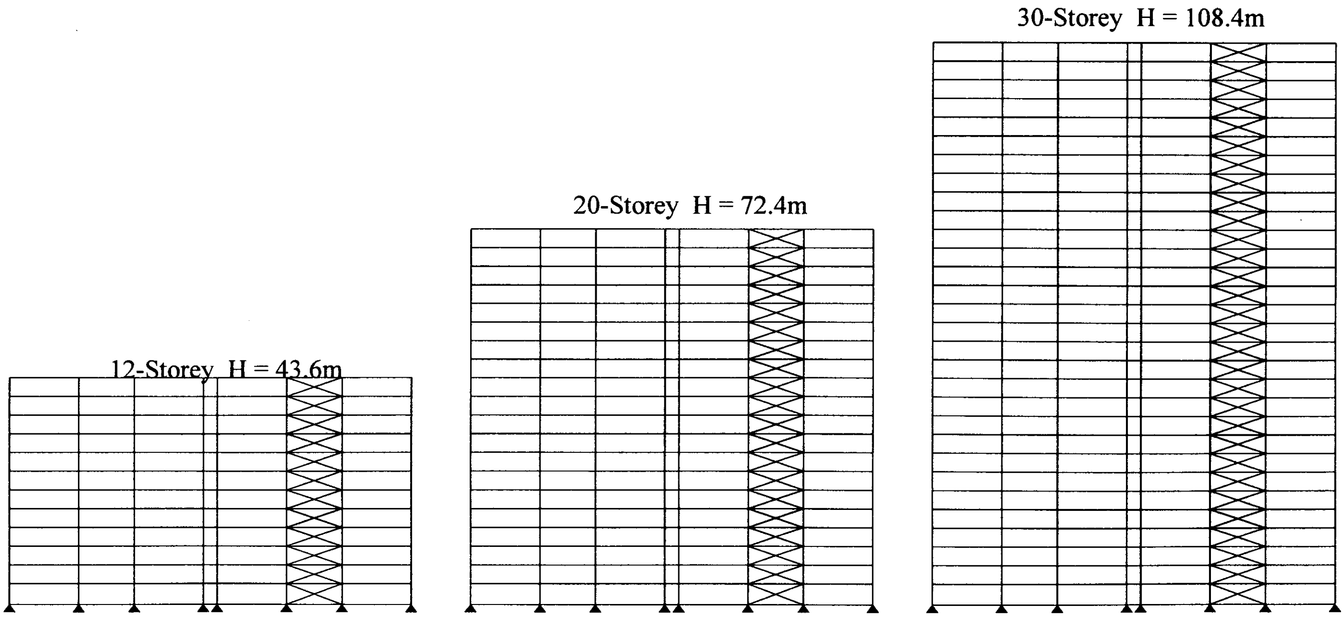



Fig. 2 Analytical model with equivalent diagonally-braced frame




(a) (b) (c)

Fig. 3 Analytical model 12-, 20-, 30-Storey

Table. 2 The section of the 12-Storey

| | □-Steel Column | | H-Steel Beam | | | |
|---|---|---|---|---|---|---|
| | H(mm) | t(mm) | H(mm) | W(mm) | $t_1$(mm) | $t_2$(mm) |
| 12S | 450 | 18 | 700 | 200 | 9 | 21 |
| 8S-11S | 450 | 18 | 750 | 300 | 16 | 26 |
| 4S-7S | 500 | 18 | 860 | 300 | 18 | 26 |
| 1S-3S | 500 | 20 | 930 | 300 | 18 | 26 |
| 0S | | | 1350 | 400 | 20 | 48 |

| | □-Eq-W-Column | | | □-Eq-W-Brace | | |
|---|---|---|---|---|---|---|
| | $H_1$(mm) | $H_2$(mm) | u | $H_1$(mm) | $H_2$(mm) | u |
| 8S-12S | 1030 | 1030 | 10% | 970 | 970 | 5% |
| 4S-7S | 1030 | 1030 | 10% | 970 | 970 | 5% |
| 2S-3S | 1330 | 1330 | 10% | 1290 | 1290 | 5% |
| 1S | 1330 | 1330 | 10% | 1260 | 1260 | 5% |

Table. 3 The section of the 20-Storey

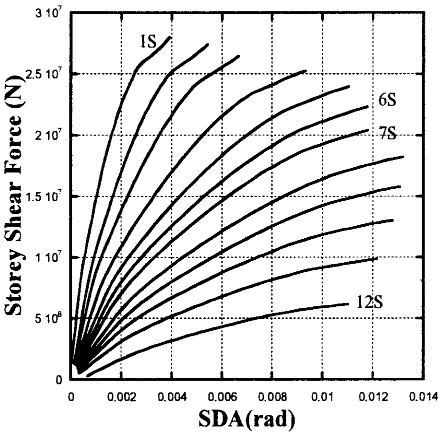
| | □-Steel Column | | H-Steel Beam | | | |
|---|---|---|---|---|---|---|
| | H(mm) | t(mm) | H(mm) | W(mm) | $t_1$(mm) | $t_2$(mm) |
| 20S | 450 | 18 | 700 | 200 | 9 | 21 |
| 15S-19S | 450 | 18 | 750 | 300 | 16 | 26 |
| 10S-14S | 500 | 20 | 800 | 350 | 17 | 30 |
| 5S-9S | 550 | 22 | 850 | 450 | 18 | 30 |
| 1S-4S | 600 | 25 | 900 | 500 | 19 | 36 |
| 0S | | | 1600 | 500 | 20 | 60 |

| | □-Eq-W-Column | | | □-Eq-W-Brace | | |
|---|---|---|---|---|---|---|
| | $H_1$(mm) | $H_2$(mm) | u | $H_1$(mm) | $H_2$(mm) | u |
| 15S-20S | 1030 | 1030 | 10% | 970 | 970 | 5% |
| 5S-14S | 1030 | 1030 | 10% | 970 | 970 | 5% |
| 2S-4S | 1330 | 1330 | 10% | 1290 | 1290 | 5% |
| 1S | 1330 | 1330 | 10% | 1260 | 1260 | 5% |

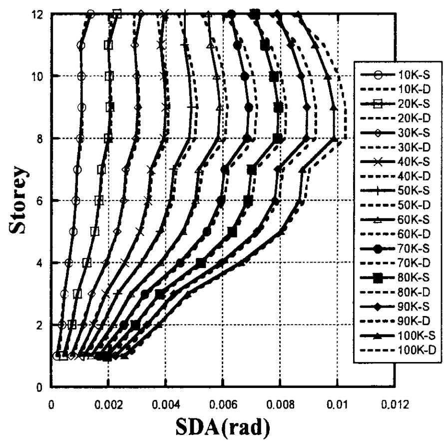
Table. 4 The section of the 30-Storey

| | □-Steel Column | | H-Steel Beam | | | |
|---|---|---|---|---|---|---|
| | H(mm) | t(mm) | H(mm) | W(mm) | $t_1$(mm) | $t_2$(mm) |
| 30S | 550 | 22 | 800 | 300 | 14 | 21 |
| 22S-29S | 550 | 22 | 800 | 400 | 18 | 38 |
| 14S-21S | 650 | 25 | 950 | 500 | 21 | 40 |
| 6S-13S | 700 | 28 | 1100 | 500 | 25 | 42 |
| 1S-5S | 800 | 32 | 1200 | 600 | 26 | 51 |
| 0S | | | 1600 | 800 | 30 | 95 |

| | □-Eq-W-Column | | | □-Eq-W-Brace | | |
|---|---|---|---|---|---|---|
| | $H_1$(mm) | $H_2$(mm) | u | $H_1$(mm) | $H_2$(mm) | u |
| 16S-30S | 1190 | 1190 | 10% | 1150 | 1150 | 5% |
| 6S-15S | 1330 | 1030 | 10% | 1290 | 1290 | 5% |
| 2S-5S | 1580 | 1580 | 10% | 1550 | 1550 | 5% |
| 1S | 1580 | 1580 | 10% | 1500 | 1500 | 5% |

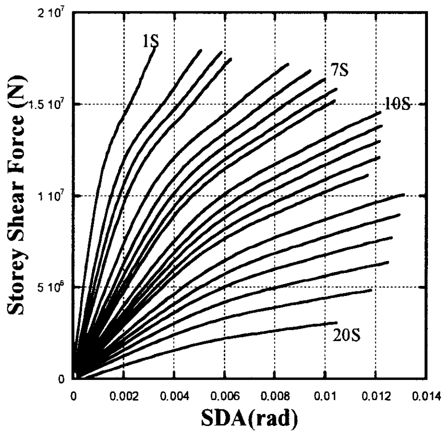


(a)

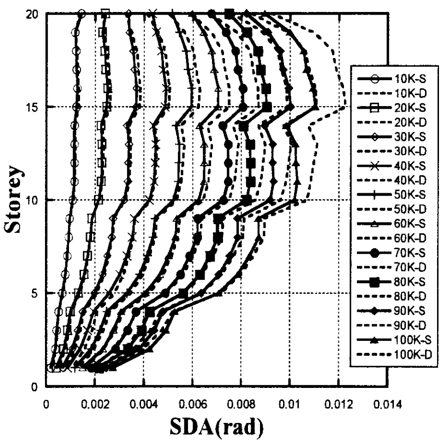


(b)

Fig. 4 The results SDA of the 12-Storey

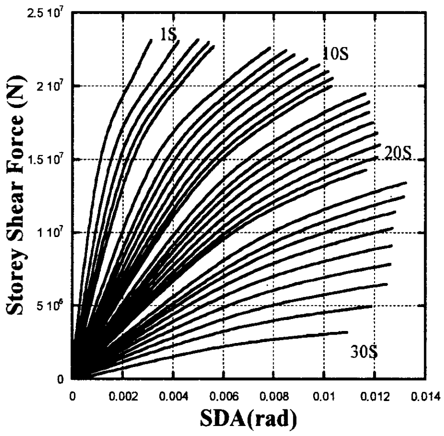


(a)

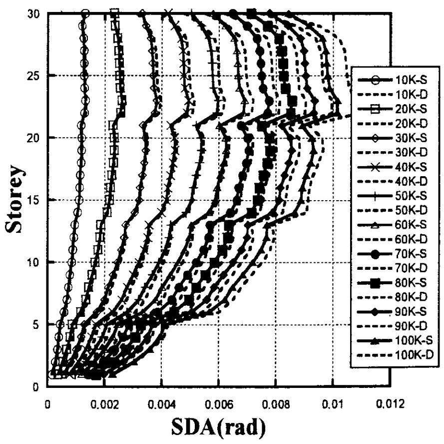


(b)

Fig. 5 The results SDA of the 20-Storey



(a)



(b)

Fig. 6 The results SDA of the 30-Storey

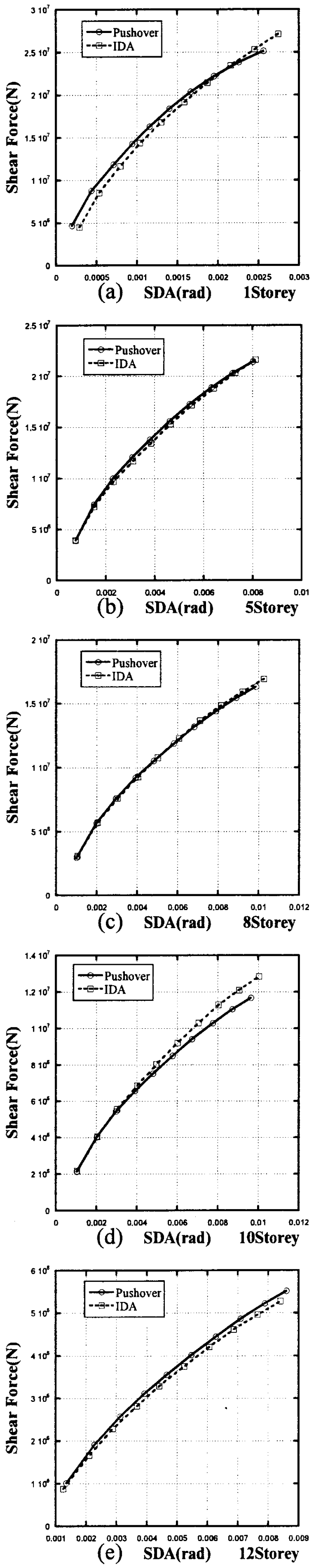



Fig. 7 The interstorey shear force 12S

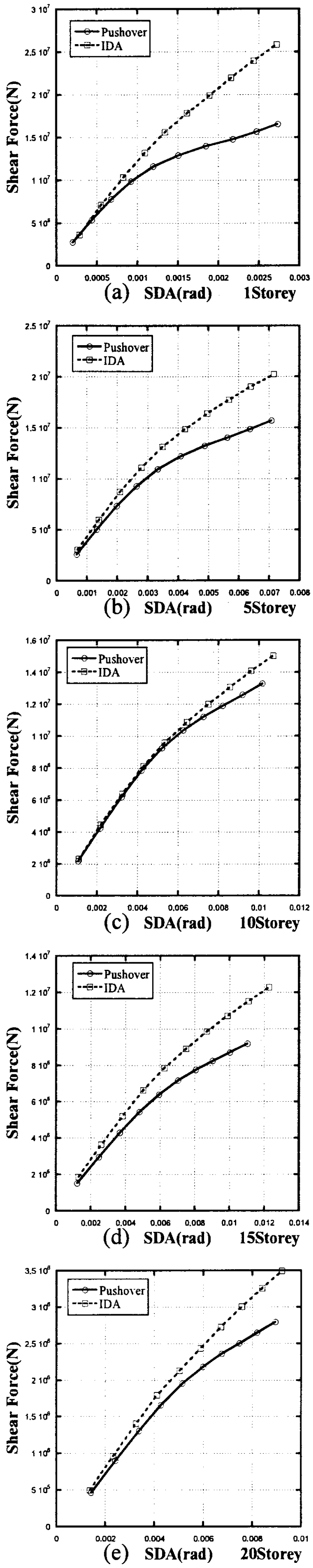



Fig. 8 The interstorey shear force 20S

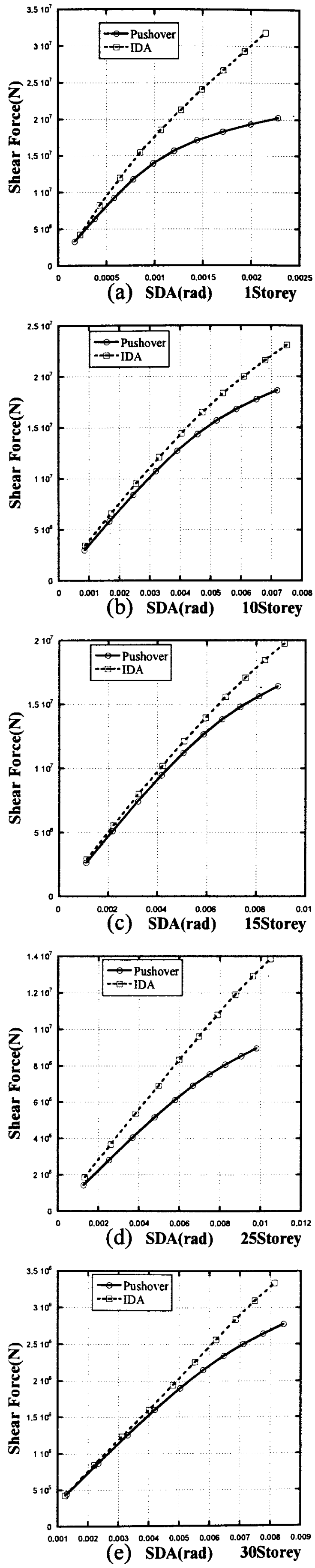



Fig. 9 The interstorey shear force 30S

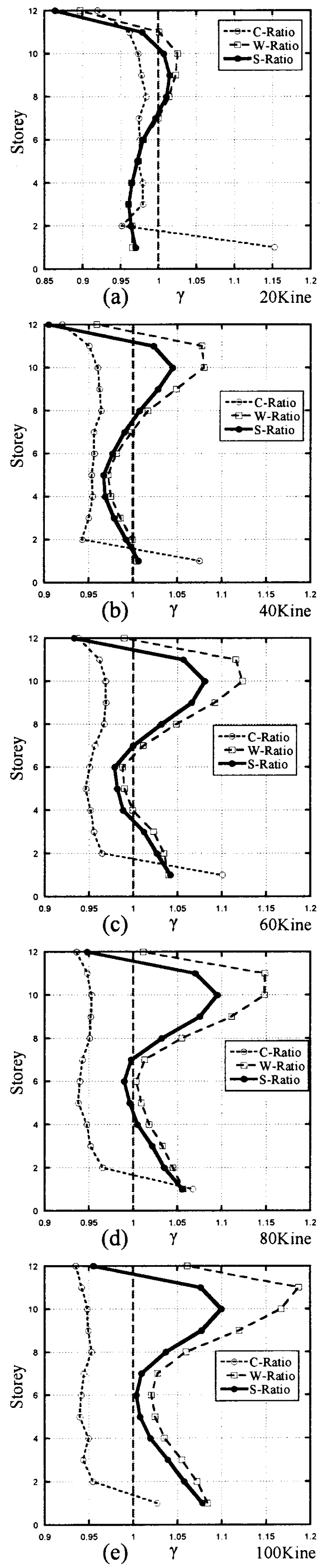



Fig.10 The amplificatory ratio γ of different intensity 12S

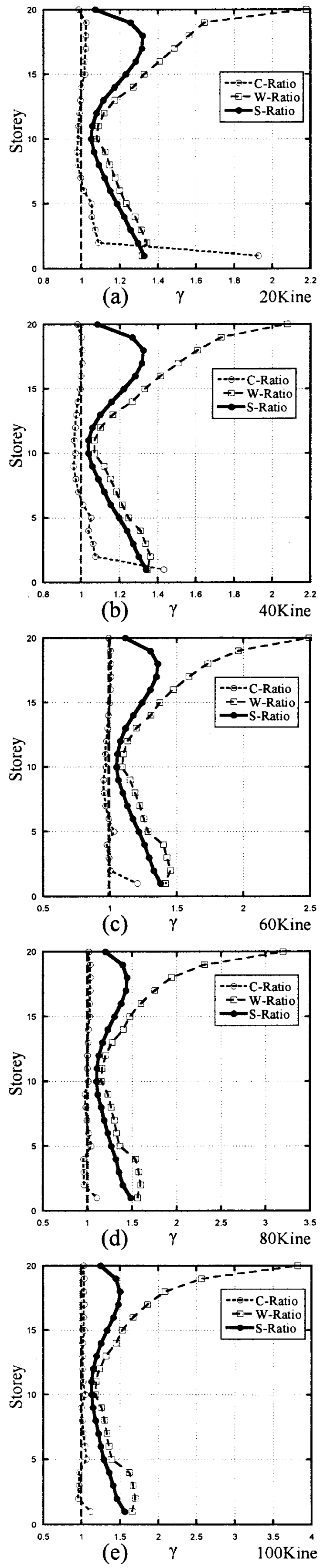



Fig.11 The amplificatory ratio γ of different intensity 20S

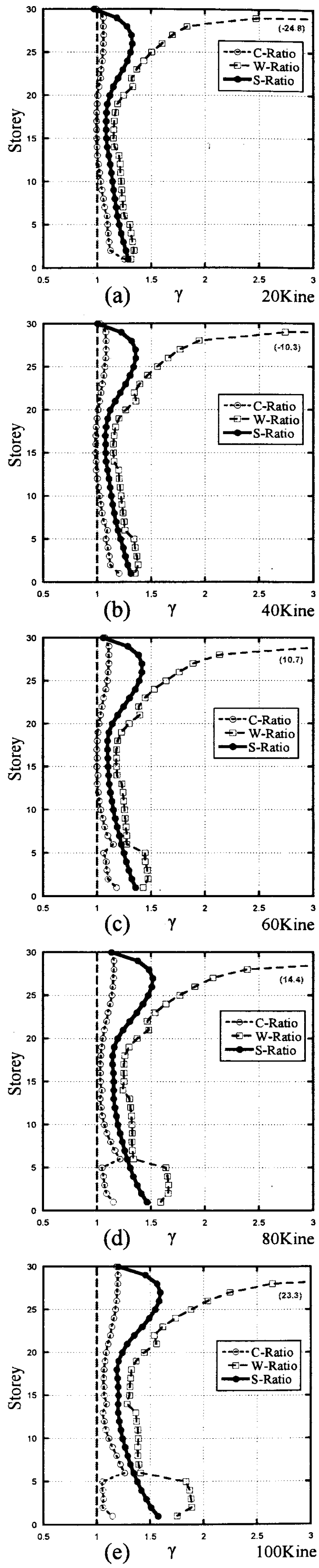



Fig.12 The amplificatory ratio γ of different intensity 30S

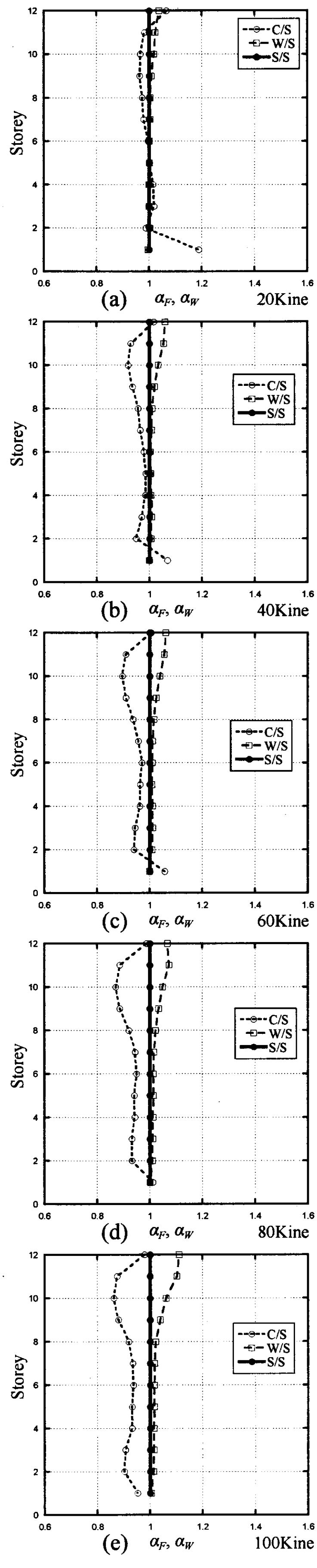



Fig.13 The ratio $\alpha$ of different intensity 12S

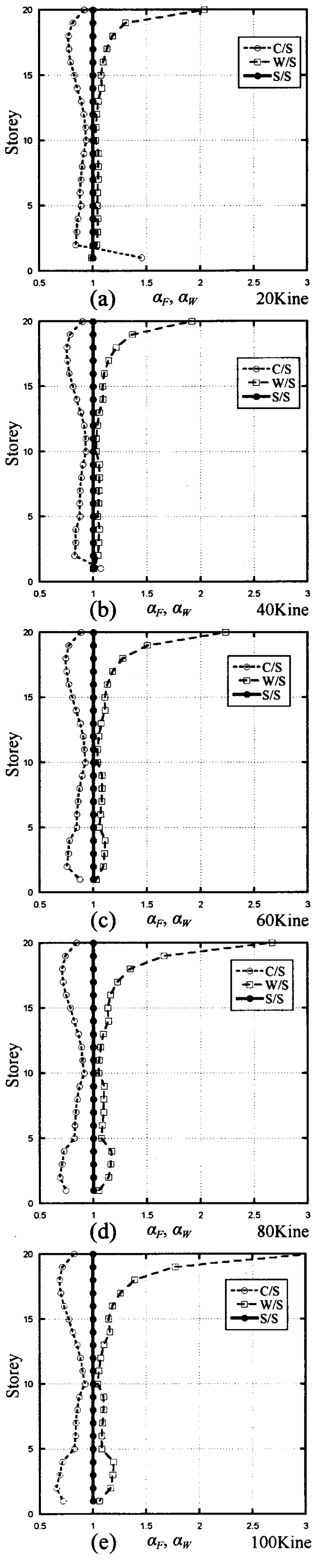



Fig.14 The ratio $\alpha$ of different intensity 20S

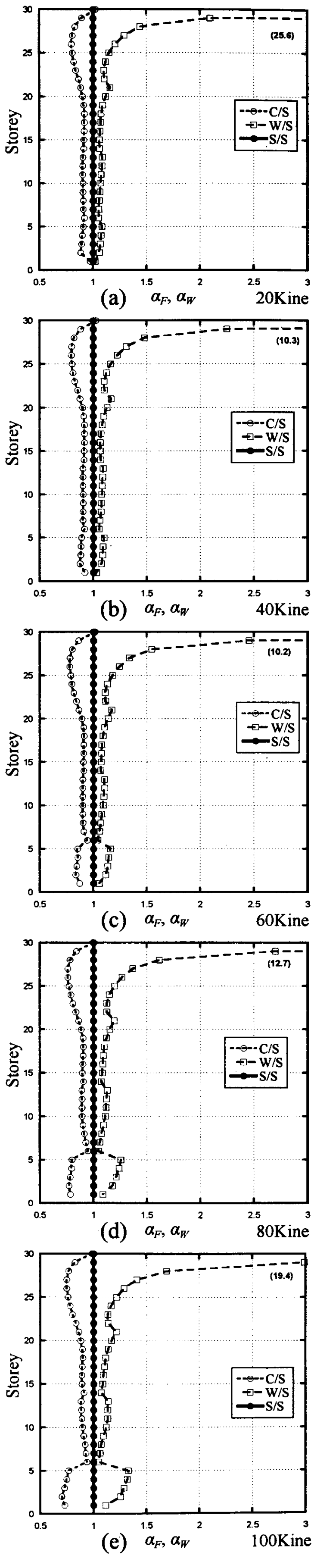



Fig.15 The ratio $\alpha$ of different intensity 30S

example, pure frame has a shear deformation pattern and reinforced concrete core wall has a bending deformation pattern, especially the core wall has a large stiffness but a very smaller deformation than pure frame, when shear wall begin to crack, the frame is still elastic, when frame begin to yield, the shear wall almost reach its ultimate status.

The behavior of this kind of hybrid structure is very complex, only static pushover analysis can't describe its behavior clearly, so dynamic analysis is needed. We modify the PGV equal to 10kine, 20kine, 30kine, 40kine, 50kine, 60kine, 70kine, 80kine, 90kine, and 100kine for each earthquake waves to change the intensity of the input ground motion, just like a dynamic pushover analysis. So we can think about the behavior of the hybrid structure in different deformation status.

In each Figure, symbol *D* means dynamic analysis result, symbol *S* means static pushover analysis result, IDA means incremental dynamic analysis result if there have no special indication. Fig. 4, 5 and 6 show the results of three different height models 12-storey, 20-storey and 30-storey, the (a) of the figures is static pushover curves for each storey, they give the essential descriptions of the capacity ability of the buildings, from elastic status to plastic status, and stiffness degradation; the figure (b) of the figures show the storey drift angle of different intensity(Average result of twenty ground motions) and static pushover analysis, while the seismic intensity changing from 10kine to 100kine, the difference between static and dynamic analysis becomes larger, because of the plastic deformation changing bigger while the seismic intensity changing higher, this phenomena has a complex relationship with the plastic character of the building and the character of the seismic records.

Fig. 7, 8 and 9 show the interstorey shear force for several storeies under pushover static analysis and incremental dynamic analysis(IDA). The figures clearly show the difference and the relationship between two kinds of analysis. Though the growth in computer processing has made possible to run a large number of dynamic analysis, but it still need much time to get the result especially the building more higher and more complex now. These figures tell us we can easily understand the behavior of the hybrid structure under seismic dynamic loads from the results of the static pushover analysis. Fig. 10, 11 and 12 will tell us the difference in detail. These figures show the amplificatory ratio $\gamma$ of different incremental intensity where the amplificatory ratio $\gamma$ equals to dynamic shear force divide static shear force($\gamma=Q_D/Q_S$). In the legends, C-Ratio, W-Ratio and S-Ratio mean ratio $\gamma_F$, $\gamma_W$, and $\gamma_S$ respectively which will be explained next. We can see the behaviors of frame columns and core shear walls are quite different. Because the deformation pattern between frame and wall is different, frames have shear deformation pattern, walls have flexure deformation pattern, the deformation pattern of the whole building have both of these two deformation character, so the behavior of frames and walls is quite different under dynamic and static analysis, the variety of the ratio $\gamma$ of frames is smoother than that of walls, the ratio $\gamma$ of walls is more sensitive, especially shear walls are the main part of the building to provide resistance against lateral forces, most of the lateral strength and stiffness is provided by walls, it's so important to understand the behavior of the building under seismic dynamic loads. While the input intensity becomes higher, the ratio $\gamma$ of the whole storey becomes larger in three different height models because of the plastic development in the model which prominently affect the behavior under seismic dynamic loads.

Usually we care the relationship of the interstorey shear force of the frame and wall with the interstorey shear force of the storey, so we standardize the fig. 10, 11 and 12. The definition is given by Eq. (1) and (2):

$$\alpha_F=\gamma_F/\gamma_S \qquad (1)$$

$$\alpha_W=\gamma_W/\gamma_S \qquad (2)$$

where

$\gamma_F$ : the amplificatory ratio of frame

$\gamma_W$ : the amplificatory ratio of wall

$\gamma_S$ : the amplificatory ratio of storey

By using Eq. (1) and (2), we get the fig. 13, 14 and 15. In the legends, the symbols C/S means ratio $\gamma_F$, W/S means ratio $\gamma_W$, The change rule of three different height models is very similar, the ratio $\alpha_F$ of the frame changes smaller, the ratio $\alpha_W$ of the wall changes larger, but it's not prominent. Below the two thirds of the height of the model, the ratio $\alpha_F$ and $\alpha_W$ almost don't changes, Upon the two thirds of the model especially the top three storeies, the ratio $\alpha_W$ of wall is very large, there are two reasons to explain this phenomena, the first is whipping effect of the model under seismic dynamic load, and the second is that the deformation pattern between frame and wall is different, frames have shear deformation pattern, walls have flexure deformation pattern, especially at the top storeys of the building. while the model is higher, the effect is more obvious. Through the ratio $\gamma$, $\alpha_F$ and $\alpha_W$, one can clearly understand and describe the behavior of the frame and wall separately under dynamic and static analysis.

## 5. Conclusive remarks

From the analytical results above paragraphs, we can get some valuable points of view to supervise the real practical design method as follows,

1. Incremental Dynamic Analysis (IDA) is a useful parametric analysis method to estimate more thoroughly structural performance under seismic loads; and it can be adopted to determine global collapse capacity of the building.
2. The rule to compare static and dynamic analysis defined in the paper part I is viable, it can be adopted in any different height buildings.
3. The result of nonlinear plastic time-history dynamic analysis is based upon the character of the seismic record we select; it's sensitive for each seismic record. Basically it's impossible to compare the result between dynamic and static pushover analysis through only one or several seismic records. One should select large numbers of records to reduce the affection of certain specific record in the statistical sense.
4. While the seismic intensity changing from minor to major, the state of building change from elastic to plastic, the difference of SDA between dynamic and static analysis becomes larger, this phenomena has a complex relationship with the plastic character of the building and the character of the seismic records. One should control the plastic development grade of the building in practical design.
5. Through the pushover and IDA curve for each storey, one can easily understand the behavior of the hybrid structure under seismic dynamic loads from the results of the static pushover analysis quickly.
6. The interstorey shear force tends to become larger under seismic dynamic loads than static pushover analysis, also it is related to input intensity of seismic records. The amplificatory ratio $\gamma$ of frame, wall and storey is different in each storey, the change rule is similar in three different height models. Through the ratio $\gamma$, $\alpha_F$ and $\alpha_W$ one can compare the interstorey shear force of frame, wall and storey under dynamic and static analysis separately.
7. According to Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept [6], when one calculates amplificatory ratio of dynamic analysis for design, one should take into account the wall ratio, in other words, the stiffness distribution between wall and frame should be taken into account. In our next research work, we will set different wall ratio to study the amplificatory ratio of wall and frame respectively basing on amplificatory ratio $\gamma$ and $\alpha$ for each storey.

## 6. Acknowledgments

This research is a part of the international cooperative program of China-Japan research on seismic performance of hybrid structures of steel-concrete in the high seismic intensity region. Many investigators are involved in this program. A large number of numerical analysis will be done on the Japanese side by the nonlinear finite element analysis program of Prof. Kawano, and some large-scale experiments will be done on the Chinese side by Xi'an Architecture Technology University, they will analyses the hybrid structure system by Ansys too.

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