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INELASTIC STATIC CHARACTERISTICS OF THE UPPER WALL-LOWER FRAME SYSTEM WITH VARIATION IN THE LOWER STORIES

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SUMMARY

The upper wall-lower frame system (mixed building structures) can be divided into three partition, namely, upper wall, lower frame, and transfer system which link two partition. These structures are characterized by an irregularity such as stiffness irregularity, mass irregularity, and vertical geometric irregularity. This study figures out seismic performance and structural behavior characteristics of the mixed building structure through pushover analyses.

The variation of lower frame stories is considered only for three types of analysis model. The conclusions of this study are following: Due to the mixed building structures fixed in the ground and a large stiffness in the transfer system, a concentrated response was made at the lower part of the lower structure in pushover analysis. Also, the plastic hinges took place earlier in ends of beam of the second story, in the base of column on the first story, and in the capital of the lower column of the transfer system successively.

INTRODUCTION

Mixed building structures of upper wall-lower frame system are usually divided by transfer system into two parts: 1) a high-rise apartment with shear wall system for residence in the upper structure, and 2) a frame structure with beam-column, which can be used as commercial spaces or parking lots in the lower structure. As they have irregularity in terms of stiffness and mass due to differences in them between upper and lower structures, mixed building structures have geometrical irregularity vertically between upper wall structure (hereinafter referred to as upper structure) and lower frame structure (hereinafter referred to as lower structure). Structures with such irregularity are called vertical irregularity structures with discontinuity, which can systematically affect the appearance of structures and lateral load resistance system [1]. Such structures are known to have concentrated responses on the lower structure under lateral load, such as displacement.

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In order to fully utilize advantages of mixed building structures, a precise and comprehensive verification about structural behavior and structural capacity under lateral load are needed. Linear elastic analysis alone is not sufficient for accurately evaluating actual capacity of these structures, but nonlinear analysis can assess capacity such as displacement of structures after yielding. Though existing studies on structural capacity of mixed building structures are mostly about nonlinear analysis of two-dimensional model and elastic analysis of three-dimensional model, there are few studies on three-dimensional response characteristics, which can generate more accurate analysis on behavior characteristics and seismic capacity of mixed building structures [2].

This paper deals with nonlinear static analysis of mixed building structures with variation in numbers of the lower stories, which is one of the factors affecting behaviors of mixed building structures. On the basis of the result of this performance, it will be made to examine plastic hinge distribution, ductility ratio and displacement distribution of upper-lower structure in the mixed building structures. This will make it possible to study seismic performance according to the changes of lower stories in the upper wall-lower frames structural system.

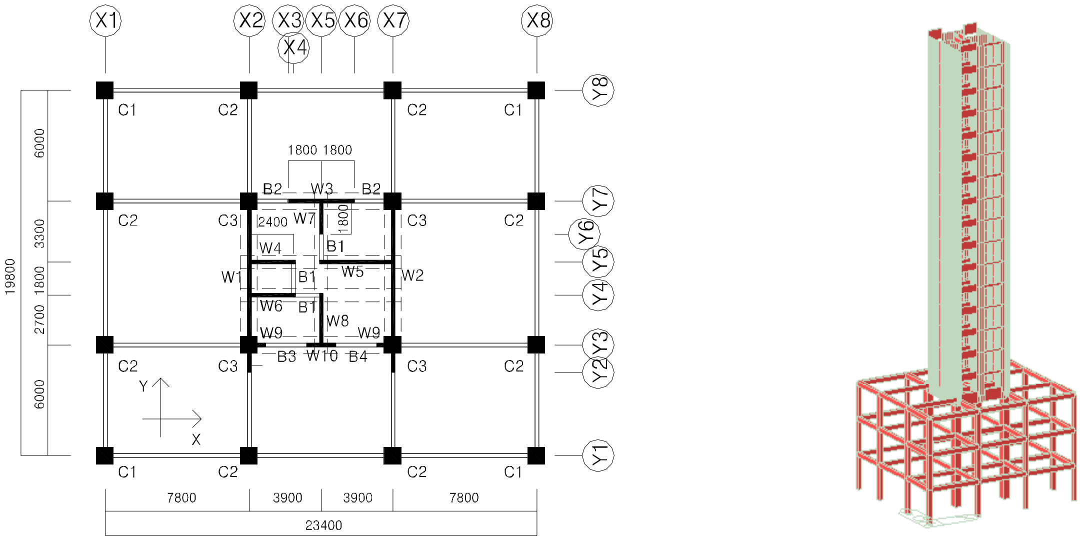
Analytical models for nonlinear behavior characteristics and seismic capacity of mixed building structures with upper wall-lower frame system are selected and the section sizes of the members and steel bar arrangement are determined by using MIDAS/GENw Ver. 4.3.2, a general-purpose program for elastic design [3]. Sectional force of each member for nonlinear analysis is calculated from elastic designed members and nonlinear static analysis on structures is conducted with CANNY 99, a general program for 3D nonlinear analysis [4][5]. The nonlinear static analysis can accurately assess the ductility of members and seismic capacity, which cannot be fully evaluated through elastic analysis, and ascertain the safety of elastic designed structures. Furthermore, the nonlinear analysis can enhance the capacity of weak members or change sections of excessively safe-designed member, therefore making the structure more safe and economical. In the pushover analysis, modal adaptive distribution (MAD) of lateral force is used to study the effect of higher modes. Roof story drift, base shear coefficient, inter-story drift and ductility ratio are evaluated in order to analyze the seismic capacity of structure and response characteristics in case of changes in the numbers of lower stories.

ELASTIC ANALYSIS AND DESIGN

Analysis model

Three analysis models selected in this study have a plan, which can be seen in Fig. 1, with same number of stories in the upper structure and different number of stories in the lower structure (Table 1). The upper structure, as a residential unit, consists of same sizes of members with same stories for all the models and its plan is referred to a generic plan actually used in Korea. The form of the transfer system is transfer girder and is drawn with dotted line in Fig. 1. The lower structure is added one span each in the direction of X and Y to the upper structure, making three spans and, therefore, has structure setback in elevation. These models are idealized models, which simplify actual mixed building structures in order to reduce calculations for nonlinear analysis, errors and complications of modeling process, and to get clear interpretation of factor analysis.

The story height for the upper structure is 2.8m, a general height for wall structures, same for all models and the story height for the lower structure is 4.5m, same for all models, reflecting the characteristics of commercial building. In assuming the sectional size of transfer girder (TG1), its height is assigned 1/10 of stories of the upper structures, and its width is approximately 35% of its height, 550×1500mm. The girders, except for TG1 of the transfer system, are designed in two separate models, i.e. G1, G2 in Fig. 1 and Table 2, but the size of members is identical. As for columns, the size of C3 columns of lower part of the upper structure is 1000×1000mm, same for all models, and the other columns (C1, C2) vary according to the model (Table 3). As for the sectional size of walls in the upper structure, the external walls are 20cm thick, and internal ones are 18cm, to correspond with the seismic design code (Table 4). Both ends of walls are reinforced with tie bar, same as columns, so that they can serve as end columns. Among characteristics of materials, the design code strength of reinforced concrete is f_{ck}=23.5MPa, the yield stress of steel is f_y=392MPa with D16 and above, f_y=294MPa with D13 and below.



(a) Plan (b) 3D structural plan

Figure 1. Graphical data of analysis models

Table 1. Numerical data of analysis models

Models	Upper Wall Story	Lower Frame Story	Total Story	Total Height (m)	Weight (kN)
ML1	16	3	19	58.3	29,420
ML2		5	21	67.3	39,053
ML3		7	23	76.3	49,524

Design load

Dead load, live load and equivalent lateral load are adapted to the initial member design among the loads for elastic analysis. Load combination of the member design of analysis model is based on the standard design loads for building of Architectural Institute of Korea [1]. Tables 2 to 4 show the member sizes and bar arrangement, which are elastically designed through using MIDAS [3], in accordance with the building code requirements for reinforced concrete of Korea Concrete Institute [6], with following load conditions. The member sizes and bar arrangement are designed to correspond with the earthquake-resistant design code, after analyzing general design data of actual buildings. As the number of stories of lower structures vary, so do the number of stories for the total structures. For all different models, the upper structures are divided into three parts; the upper level (seven stories), the middle level (six stories), and the lower level (three stories), as seen in Table 4.

Dead load and live load in the case of upper wall structure are assumed as 5.88kPa and 1.96kPa, respectively. Dead load and live load in the lower frame structure are assumed as 5.49kPa and 3.43kPa, respectively. To calculate equivalent seismic load by the standard design code, seismic coefficient (A) 0.11, occupancy importance factor (I_E) 1.5, site coefficient (S) 1.0, response modification factor (R) 3.0 are assigned. The formula for vibration period of other structural systems is used for the fundamental period.

Table 2. Beam list

Models	Gir. ID	Story No.	Size(mm)	Main bars		Stirrups	
				End	Cent.	End	Cent.
ML1	G1	2F-Pit	400×600	6-HD22	2-HD22	D10@200	D10@250
				2-HD22	3-HD22		
	G2	2F-Pit	400×600	8-HD25	2-HD25	D10@200	D10@250
				2-HD25	3-HD25		
ML2	G1	2F-Pit	400×600	8-HD22	3-HD22	D10@200	D10@250
				4-HD22	3-HD22		
	G2	2F-Pit	400×600	7-HD29	2-HD29	D10@200	D10@250
				3-HD29	3-HD29		
ML3	G1	2F-Pit	400×600	8-HD22	3-HD22	D10@200	D10@250
				4-HD22	3-HD22		
	G2	2F-Pit	400×600	8-HD29	3-HD29	D10@200	D10@250
				3-HD29	5-HD29		
ML1-ML3	TG1	Pit	550×1500	11-HD29 (all)		HD19@200, HD19@200*	
				11-HD29 (all)			
B1(180×580), B2(180×1300), B3(180×1000), B4(180×320); Top bars: 4-HD16, Bottom bars: 4-HD16, Stirrups: D10@200 (all) * Horizontal shear reinforcement							

Table 3. Column list

Models	Col. ID	Story No.	Size(mm)	Main bars	Ties
ML1	C1, C2	1F-Pit	600×600	12-HD22	D10@200
	C3	1F-Pit	1000×1000	32-HD25	D10@200
ML2	C1, C2	1F-Pit	700×700	14-HD22	D10@200
	C3	1F-Pit	1000×1000	40-HD25	D10@200
ML3	C1, C2	1F-Pit	800×800	18-HD22	D10@200
	C3	1F-Pit	1000×1000	42-HD25	D10@200

Table 4. Wall list

Wall ID	Thk. (㎜)	Story No.*	ML1		ML2		ML3		ML4		Edge Bar
			Ver.Bar**	Hor.Bar**	Ver.Bar**	Hor.Bar**	Ver.Bar**	Hor.Bar**	Ver.Bar**	Hor.Bar**	
W1, W2	200	Upper	D10@400	D10@300	D10@400	D10@400	D10@400	D10@400	D10@400	D10@400	4-HD16
		Middle	D10@400	D10@300	D10@200	D10@200	D10@200	D10@200	D10@200	D10@200	4-HD16
		Lower	D13@400	D10@200	D13@200	D10@200	D10@200	D10@200	D13@200	D10@200	4-HD16
W3	180	Upper	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	D10@300	D10@300	4-HD16
		Middle	D10@400	D10@300	D13@400	D10@300	D10@400	D10@300	D10@300	D10@300	4-HD16
		Lower	D13@300	D10@300	D13@200	D10@300	D10@200	D10@300	D13@200	D10@300	4-HD16
W4, W6, W8	180	Upper	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	4-HD16
		Middle	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	4-HD16
		Lower	D13@150	D10@250	D16@150	D10@150	D16@150	D10@150	D16@150	D10@150	4-HD16
W5	180	Upper	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	4-HD16
		Middle	D10@300	D10@300	D13@200	D10@300	D10@200	D10@300	D13@200	D10@300	4-HD16
		Lower	D13@100	D10@150	D16@100	D13@150	D16@100	D13@150	D16@100	D13@150	4-HD16
W7	180	Upper	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	4-HD16
		Middle	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	D10@400	D10@300	4-HD16
		Lower	D10@400	D10@300	D13@400	D10@300	D10@200	D10@300	D10@200	D10@300	4-HD16
W9-W11	180	Upper	D13@150	D10@300	D13@150	D10@300	D13@150	D10@300	D13@150	D10@300	4-HD16
		Middle	D13@150	D10@300	D13@150	D10@300	D13@150	D10@300	D13@150	D10@300	4-HD16
		Lower	D13@150	D10@300	D13@150	D10@300	D13@150	D10@300	D13@150	D10@300	4-HD16

* Upper, middle, lower is seven stories of upper level, six stories of middle level, and three stories of lower level in the upper wall..
** Double

NONLINEAR ANALYSIS

Basic hypothesis

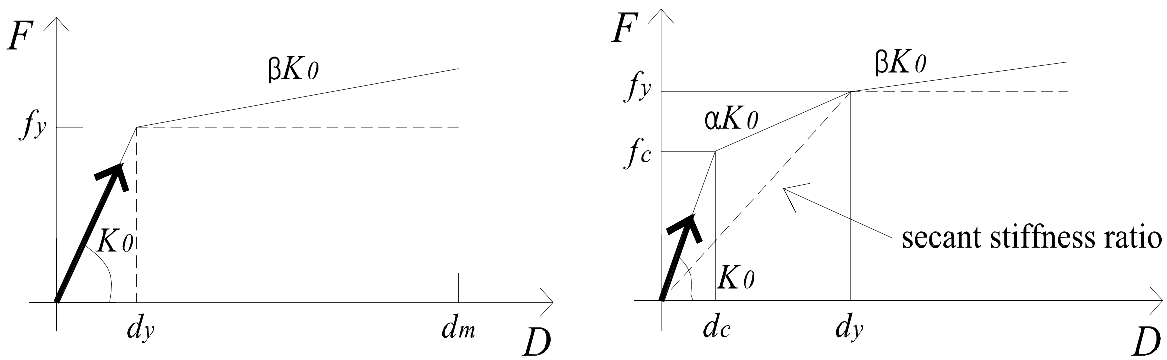
Three-dimensional analysis models are used in order to understand nonlinear response of buildings, assuming that structure is fixed on the foundation, while each story is under the action of rigid diaphragm. P-Δ effect is also considered. The beam-column joint is assumed rigid and linear element ends are presented by rigid zones. The self weights of the structures are considered as initial weights before conducting the nonlinear analysis, as well as MAD lateral load distribution are used to study the effects of higher modes.

Characteristic of element model

The line element (beam and column) in nonlinear analysis can be idealized by elasto-plastic uniaxial spring through two rotational spring at element ends and shear and axial springs located in mid span. Axial deformation of beam is not taken into consideration and that of column is regarded as elastic deformation. It is assumed that in the case of the shear wall model, rigid panel-beam with infinite stiffness is located at top and bottom of the shear wall. Uniaxial bending spring, axial spring and shear spring are used to show the panel deformation in the panel plane and out-of-plane stiffness is ignored.

Skeleton curve and hysteresis rule

The skeleton curve used in this study, a bilinear model (Fig. 2(a)) is used in the flexural deformation, tri-linear model (Fig. 2(b)) is used in the shear deformation, and elastic model is used in the axial deformation. As for flexural deformation is assigned bilinear model as seen in Fig. 2(a), the stiffness ratio after yielding is computed with the flexural theory of reinforced concrete members. The secant stiffness ratio at the shear yielding point, for calculating the stiffness ratio after cracking of shear deformation (α) and the stiffness ratio after yielding (β), is supposed to be 0.16 of the initial elastic stiffness, and the stiffness after shear yielding is set as 0.001 of the initial elastic stiffness [7]. In the case of the shear deformation of beam, column, and shear wall, cracking strength and yielding strength are considered for tri-linear model.



(a) Bilinear curve (b) Tri-linear curve

Figure 2. Skeleton curve

Pushover analysis

The pushover analysis can be viewed as a method that can precisely follow the process of yielding hinge of members and the story yielding situation of the whole structure and, also, identify critical members which can reach ultimate state by seismic force. The pushover analysis is an appropriately simplified nonlinear dynamic analysis for capacity assessment of structures, but it has shortcomings in terms of adequacy of the distribution pattern selection of lateral load. As for the method of the distribution of lateral force, the modal adaptive distribution (MAD) [9], which can consider the effect of higher mode, is used and the lateral force by the MAD method can be seen in Eq. (1).

$$F_i = \frac{M_i\left[\sum_{j=1}^{m}(\phi_{ij}\Gamma_j)^2\right]^{1/2}}{\sum_{l=1}^{n}M_l\left[\sum_{j=1}^{m}(\phi_{lj}\Gamma_j)^2\right]^{1/2}}V \quad , \quad \Gamma_j = \frac{\sum_{i=1}^{n}M_i\phi_{ij}}{\sum_{i=1}^{n}M_i\phi_{ij}^2} \tag{1}$$

Where,

n : number of stories

m : number of modes

ϕ_{ij} : mode shape at i-th level and j-th mode

Γ_j : j-th modal participation factor

M_i : mass of i-th story

V : base shear

In the analysis, the lateral force is applied only in the direction of X (Fig. 1), and lateral load increases gradually in accordance with its degree to prevent the occurrence of rapid stiffness change.

RESULTS OF ANALYSIS AND INVESTIGATION

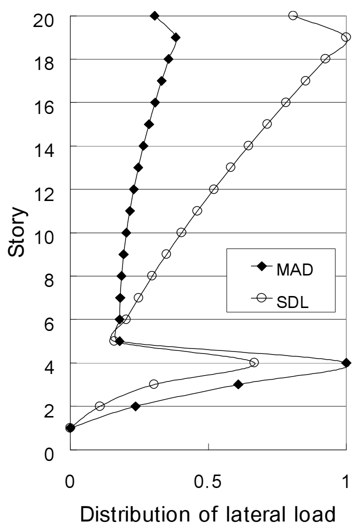
The results of elastic analysis and the distribution of lateral load

Table 5 shows the natural period of direction X calculated by MIDAS's and CANNY's analysis model, and also shows the modal participation factor by MIDAS's analysis model. As the stories of lower structures increase, the modal participation factors of the third mode increase. It is believed that the effect of higher mode becomes stronger as the lower stories increase.

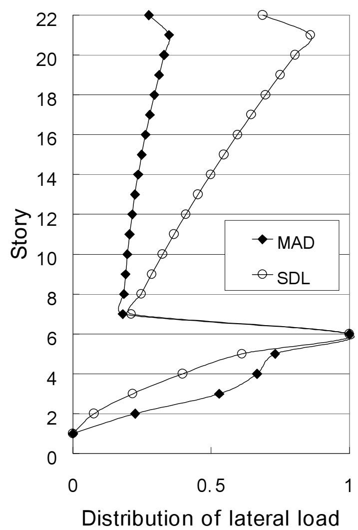
Table 5. Result of elastic analysis

Models	Mode	Period		Error ratio (%)	Modal participation factor (MIDAS)
		MIDAS	CANNY		
ML1	1st	1.58	1.58	0.0	0.573
	2nd	0.63	0.63	0.0	0.339
	3rd	0.24	0.26	-7.7	0.088
ML2	1st	1.98	1.98	0.0	0.568
	2nd	0.89	0.91	-2.2	0.253
	3rd	0.32	0.32	0.0	0.179
ML3	1st	2.40	2.40	0.0	0.587
	2nd	1.09	1.10	-0.9	0.223
	3rd	0.48	0.45	6.7	0.190
Where, error ratio(%)= (MIDAS – CANNY) / CANNY $\times$ 100, modal participation factor= $\Gamma_j / \sum_{i=1}^{3} \Gamma_i$					

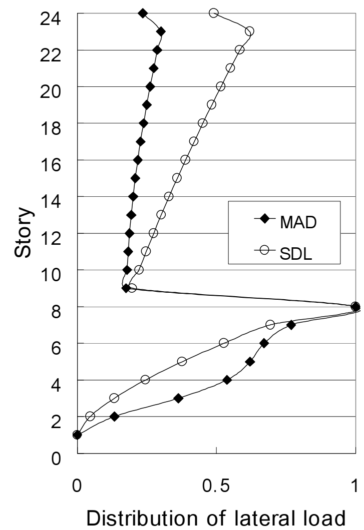
Fig. 3 shows the distribution of story lateral load of the equivalent lateral load according to the standard design loads (SDL) and the distribution according to MAD, considering higher mode effect [9]. As you can see in the figure, the distribution patterns are different according to the lateral load pattern. It is desirable to use the MAD pattern, which can consider the effect of higher mode in case of mixed building structure with high irregularity.



(a) ML1



(b) ML2



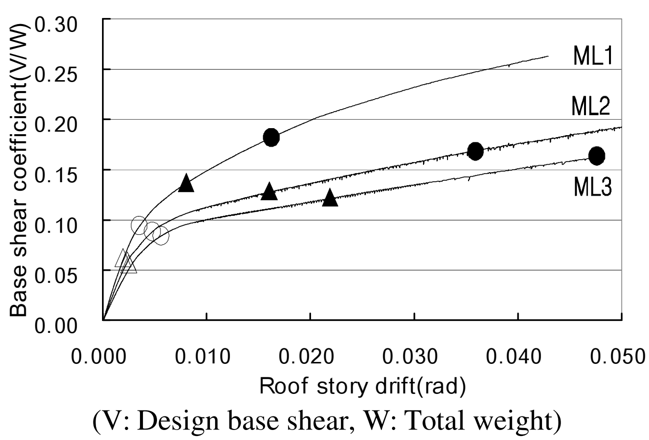
(c) ML3

Figure 3. Distribution of lateral forces

Pushover analysis

Roof story drift and base shear coefficient

As the result of pushover analysis on analytical models, the relationship between the base shear coefficient and the roof story drift, which indicates the ratio of roof story displacement to the total height of the structures, is shown in Fig. 4. The signs of △, ○, ▲, ● of the figure are results from the acting of V, 2V, 3V, 4V base shear forces, respectively, for each model, according to the earthquake resistant design standards.



(V: Design base shear, W: Total weight)

Figure 4. Roof story drift-base shear coefficient

As Fig. 4 shows, increased lower stories reduce the base shear coefficient, while increasing the roof story drift. As lower stories increase, both the total weight of the structure (W) and the design base shear (V) increase accordingly, while the increased period leads to the reduced seismic coefficient (C). Therefore, the base shear coefficient (V/W) decreases, for the growth rate of design base shear becomes smaller than that of the total weight of the structure. It is also considered that added lower stories bring about further inter-story displacement of frame structures, which are less stiff than shear walls, increasing the roof story drift.

Inter-story drift

Figs. 5 to 7 and Tables 6 to 7 show the results of the pushover analysis when the roof story drift reaches to 1/200 radian. The roof story drift represents the ratio of displacement of roof story to its height. This drift refers to Eq. 2, for allowable inter-story displacement required by the standard design loads (in Korea) [1]. Allowable inter-story drift comes to 1/200 radian, when Eq. 2 is converted to inter-story drift, considering nonlinear behaviors of structures.

$$\Delta_a = 0.015\, h_{sx} \geq R(\delta_x - \delta_{x-1}) \quad (2)$$

where,

Δ_a: Allowable inter-story displacement

h_{sx}: Story height

R : Response modification factor

δ_x : Story displacement

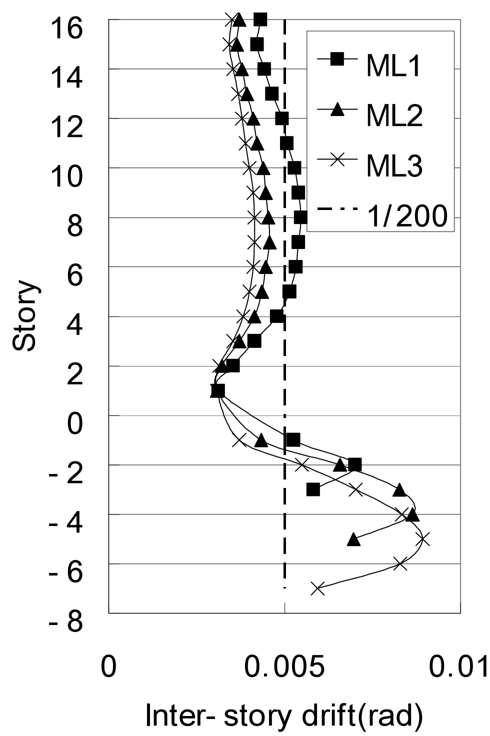


Figure 5. Inter-story drift

The stories of lower structures are different between models and those of upper structures are the same (16 stories). Therefore, in Fig. 5 to 7, the upper stories are the same 16 stories, with the same transfer system as the first story. The number of lower stories reduces, as they become lower under the transfer system. The lower stories in Table 6 and 7 show actual number of stories.

Fig. 5 shows the distributions of inter-story drift for each model. It is clearly shown that as lower stories increase from the ML1 model to the ML3 model, the inter-story drift for lower structure increases, particularly, above middle part of lower stories, while that for upper structure generally decreases. The reason is that the increase of lower stories of frame structure, which are less stiff than upper structure with shear walls, leads to displacement in lower structure, but reducing that of upper structure.

Ductility ratio

Ductility ratio is one of the parameters, through which structural member's state can be examined, and is defined by the ratio of maximum response displacement to yielding displacement. If it is above 1, then plastic hinges appear, if below 1, elastic state is kept.

Tables 6 to 7 and Figs. 6 to 7 show the flexural ductility ratio of members for each different case of lower stories. Table 6 shows the flexural ductility ratio of both ends for girders G2 (X2-X7, Y3) in lower structure. The maximum flexural ductility ratio of right end of girder (ML1; 7.17, ML2; 4.19, ML3; 2.42) decreases as lower stories increase. Table 7 shows the flexural ductility ratios of the top of columns below the transfer system and the base of columns of the first story. It is shown that, as in case of girders, the ratio of columns decreases with added lower stories. It is considered that the ratio for right end of the lower structure girders is large, due to the effect of the direction of lateral forces (direction X in Fig. 1). The reason for the reduced flexural ductility ratios for beams and columns in lower structure with increased stories is that the quantity of steel in beams and columns in elastically designed lower structure increases as stories increase from ML1 to ML3. Also, in the distribution of lateral forces the maximum lateral force is generated at the transfer system and the differences in load distribution between neighboring stories (Fig. 3) are reduced.

Table 6. Flexural ductility ratio of both ends for girders G2 (X2-X7, Y3)

<table>
<tr><th colspan="3">ML1</th><th colspan="3">ML2</th><th colspan="3">ML3</th></tr>
<tr><th>Story</th><th>Left end</th><th>Right end</th><th>Story</th><th>Left end</th><th>Right end</th><th>Story</th><th>Left end</th><th>Right end</th></tr>
<tr><td rowspan="6">3F</td><td rowspan="6">3.56</td><td rowspan="6">1.24</td><td rowspan="3">5F</td><td rowspan="3">1.00</td><td rowspan="3">0.95</td><td rowspan="2">7F</td><td rowspan="2">0.43</td><td rowspan="2">0.70</td></tr>
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<tr><td rowspan="2">6F</td><td rowspan="2">0.77</td><td rowspan="2">0.93</td></tr>
<tr><td rowspan="3">4F</td><td rowspan="3">1.91</td><td rowspan="3">1.28</td></tr>
<tr><td rowspan="2">5F</td><td rowspan="2">0.98</td><td rowspan="2">1.25</td></tr>
<tr></tr>
<tr><td rowspan="6">2F</td><td rowspan="6">0.46</td><td rowspan="6">7.17</td><td rowspan="3">3F</td><td rowspan="3">0.61</td><td rowspan="3">4.19</td><td rowspan="2">4F</td><td rowspan="2">0.67</td><td rowspan="2">2.38</td></tr>
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<tr><td rowspan="2">3F</td><td rowspan="2">0.68</td><td rowspan="2">2.42</td></tr>
<tr><td rowspan="3">2F</td><td rowspan="3">0.55</td><td rowspan="3">3.80</td></tr>
<tr><td rowspan="2">2F</td><td rowspan="2">0.59</td><td rowspan="2">2.04</td></tr>
<tr></tr>
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Table 7. Flexural ductility ratios of columns C3 (X7, Y3)

Position	ML1	ML2	ML3
Top of columns below the transfer system	5.63	2.53	1.93
Base of columns of the first story	6.09	4.93	4.85

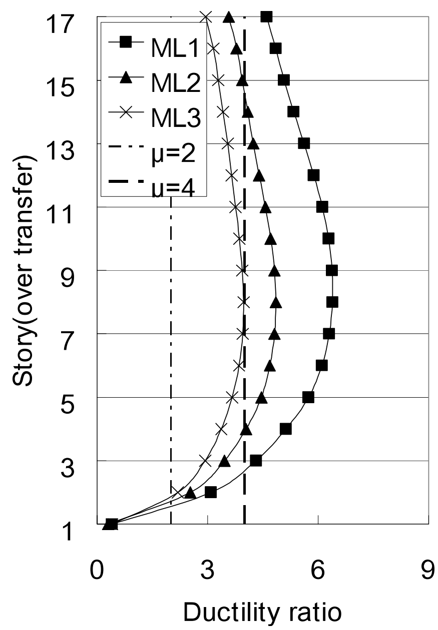
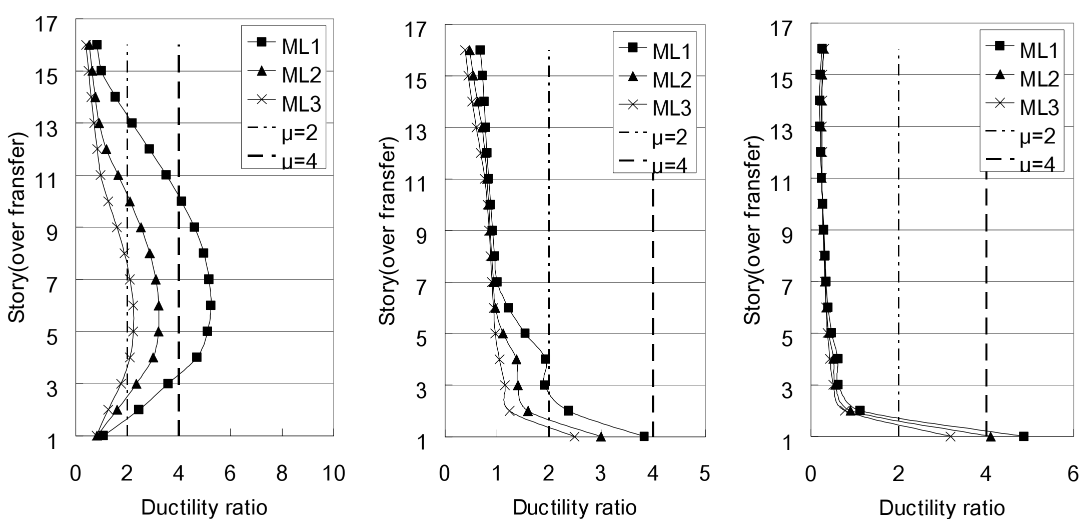


Figure 6. Flexural ductility ratio for right end of beams B4 of row Y3 (upper structure)



(a) W9 (b) W10 (c) W11

Figure 7. Flexural ductility ratio for right end of beams B4 of row Y3 (upper structure)

Figs. 6 to 7 show the distribution of the flexural ductility ratio for right end of coupling beams of upper structure (B4) and the bottom of shear walls (W9 to W11), and it's seen that the ratio decreases as lower stories increase. There is no effect from bar arrangement of steel, for the arrangement for coupling beams and shear walls is identical for all models. It is considered the increased lower stories reduce the flexural ductility ratio for members of upper structure. At Fig. 6, it' is shown that coupling beam B4 is very vulnerable to lateral load. As for shear walls, the distributions of the flexural ductility ratios are different according to the location of the walls. For example, shear wall W9 (Fig. 7(a)) shows ductility ratios in the middle stories for all models, and W10 (Fig. 7(b)) and W11 (Fig. 7(c)) have concentrated ductility deformation at the lowest end of the upper part of the transfer system. Such difference in the flexural ductility ratio for walls is considered to be due to the effect of walls in the direction Y, crossing these walls in the direction X. Fig. 1 shows that W9 of row Y3 has W1 in the direction Y, attached to the tensile side of it, while W11 has W2 in the direction Y attached to the compression side of it. Therefore, W9 has not yet had a yielding of the tensile steel at the bottom of the wall, while W11 has already experienced a yielding of the tensile steel at the same location.

CONCLUSIONS

In this study, a mixed building structure with upper wall-lower frame system, which has transfer girder for transfer system, is selected to analyze its response characteristics in case of varied lower stories, through nonlinear analysis on three-dimensional mixed building structure. Through the analysis, the following results are produced.

1) As the result of pushover analysis of structure such as roof drift (i.e. roof displacement/structural height) and base shear coefficient, when the stories of lower frame system are increased, base shear coefficient is decreased, but roof drift is increased.

2) According to an increase in stories of the lower frame, story drift and ductility ratio of upper wall system is decreased and behavior of upper wall system is closed to elastic.

3) As the result of pushover analysis, it is shown that added lower stories lead to concentrated increase of inter-story drift in lower structure, but, with increased steel quantity in lower columns and beams, the ductility ratio of lower structure decreases and considerable flexibility for lower structure is secured.

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