SEISMIC PERFORMANCE ESTIMATION OF ASYMMETRIC BUILDINGS BASED ON THE CAPACITY SPECTRUM METHOD

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SUMMARY

This paper presents the procedure for seismic performance estimation of asymmetric buildings based on a concept of the capacity spectrum method. In order to evaluate the torsional effect due to plan asymmetry to inelastic seismic responses of asymmetric buildings, the strength modification factor and the deformation amplification factor are introduced. The strength modification factor is used to quantify the decrease of strength capacities to horizontal seismic forces of asymmetric-plan stories, considering strength eccentricities and torsional strength capacities. The deformation amplification factor is used to quantify the amplification of story drifts in the damage-predicted sides of asymmetric-plan stories, based on linear and static three-dimensional analysis. The proposed procedure using these factors is verified by parametric studies for inelastic responses of three-story asymmetric building's models with some types of asymmetric-plan stories using a step-by-step time integration method. The asymmetric plans are classified into the rigidity-strength eccentric type, the rigidity eccentric type or the strength eccentric type. It is concluded that the torsional effect can be evaluated by using two above-mentioned factors regardless of the eccentric type of asymmetric plans, and a concept of the capacity spectrum method can be applied to asymmetric buildings by introducing these factors.

INTRODUCTION

Performance based design codes for building structures are now on going to be prepared in Japan. And it may be the current trend in the world. For introducing the performance based design codes, practical procedures for performance estimation of buildings need to be developed and generalized. As one of such the procedures, the capacity spectrum method [Freeman, 1978] is remarked, now. However, further investigation is necessary in order to apply this method to asymmetric buildings, because the torsional effect due to plan asymmetry is not evaluated appreciatively so far.

In the capacity spectrum method, the multi-story buildings are converted into the equivalent single degree of freedom (1-DoF) systems based on the outputs of pushover analysis. And the structural performance of buildings is represented by a base share versus horizontal displacement relationship of the equivalent 1-DoF systems. The relationship is refereed to as the capacity spectrum. If a multi-story building is symmetric, the capacity spectrum is obtained by calculating the spectral response acceleration (*Sa*) by using Equation (1) and the spectral response deformation (*Sd*) by using Equations (2) and (3) through every analysis step of pushover analysis [Kuramoto et.al., 1999]. And the multi-story building is converted into the equivalent 1-DoF system.

$$S_a = \sum_{i=1}^{N} m_i \cdot \delta_i^{\,2} \bigg/ \left(\sum_{i=1}^{N} m_i \cdot \delta_i \right)^2 \cdot Q_B \tag{1}$$

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$$S_d = S_a / \omega^2 \tag{2}$$

$$\omega^2 = \sum_{i=1}^{N} P_i \cdot \delta_i \Big/ \sum_{i=1}^{N} m \cdot \delta_i^2 \tag{3}$$

in which m_i = mass of each story; δ_i = displacement of each story; Q_B = base shear; and P_i = horizontal seismic force of each story.

In the other hand, the seismic design spectra are expressed as the demand spectra, which show the relationship between the *Sa* and the *Sd* of elastic 1-DoF systems with some viscous damping ratios. And the seismic response of the building can be evaluated as the intersection refereed to as the performance point between the capacity spectrum and the demand spectrum for the equivalent viscous damping ratio of the building, as shown in Figure 1. Each story's drift of the multi-story building is predicted by extracting each story's output by pushover analysis corresponding to the performance point. The seismic performance is estimated by comparing these predicted values with the values for the Limit State of the system.

In order to apply this method to asymmetric buildings, the torsional effect must be considered when calculating the capacity spectrum and predicting each story's drift, which is amplified in each story's damage-predicted side. In this study, to evaluate the torsional effect, the strength modification factor and the deformation amplification factor are introduced based on the previous work [Ozaki et.al., 1994]. And the procedure for seismic performance estimation using these factors is verified by parametric studies for inelastic responses of three-story asymmetric building's models with some types of asymmetric-plan stories.

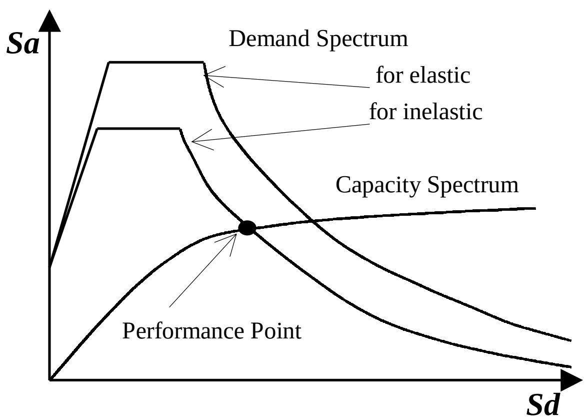


Figure 1 : Capacity Spectrum and demand spectrum

EVALUATION OF THE TORSIONAL EFFECT

In general, the inelastic story drift of symmetric buildings is presented as the ductility factor μ by using Equation (4).

$$\mu = \delta_N / \delta_y \tag{4}$$

in which δ_N= the inelastic story drift due to major ground motions (EQ-2 level); and δ_y= the yield story drift.
The ductility factor μ can be also expressed by using Equation (5) according to the force-deformation relationship of symmetric buildings as shown in Figure 2.

$$\mu = \frac{\alpha \cdot \delta_N}{\delta_E \cdot R} \tag{5}$$

in which α=the ratio of moderate earthquake ground motions (EQ-1 level) to EQ-2 level; δ_E= the linear story drift due to EQ-1 level; and *R*=the ratio (the shear strength capacity ratio) of the shear strength capacity Q_p to the corresponding linear shear force Q_L, when a system is assumed to be elastic without yielding.

The concept of the shear strength capacity ratio *R* in Figure 2 and Equation (5) can be extended to asymmetric buildings using the shear and torsional strength capacity ratio *eR* [Ozaki et.al., 1994]. That is,

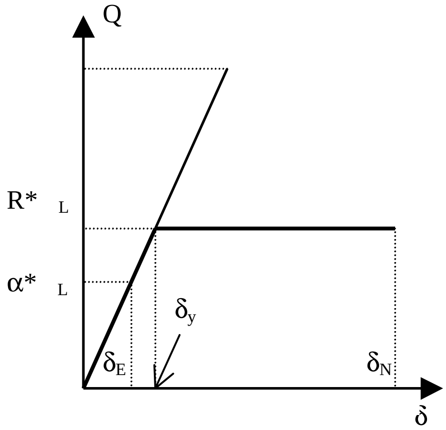


Figure 2: Force-deformation relationship of symmetric system

$$eR_x = \frac{1}{\dfrac{Q_{Lx}}{Q_{Px}} + \dfrac{\left|T_{Lx} + 0.5 \cdot T_{Ly}\right|}{T_{P\theta}}} \tag{6}$$

in which eR_x =the shear and torsional strength capacity ratio in the x-direction; T_{Lx}= the torsional moment obtained by multiplying Q_{Lx} by the strength eccentricity *fy*, which is a distance between the center of the shear force and the center of strength in the y-direction; T_{Ly} = the torsional moment obtained by multiplying Q_{Ly} by the strength eccentricity *fx* in the x-direction; and $T_{p\theta}$= the torsional strength capacity.

The shear and torsional strength capacity ratio *eR* is derived from a concept of a strength capacity surface, which reveals strength capacities of asymmetric systems subjected to earthquake ground motions in the x- and y-directions, simultaneously. Using the shear and torsional strength capacity ratio *eR*, inelastic story drift δ_{Nperi} at the perimeter in the damage-predicted side of asymmetric buildings can be expressed as μ_{peri} by using Equation (7), which corresponds to μ of symmetric buildings expressed by Equation (5).

$$\mu_{peri} = \frac{\alpha \cdot \delta_{Nperi}}{\delta_{Eperi} \cdot eR} \tag{7}$$

in which δ_{Eperi}= linear story drift due to EQ-1 level at the perimeter in the damage-predicted side.

It has been verified that the relationship between *eR* and μ_{peri} of the asymmetric systems is comparable with the relationship between *R* and μ of the corresponding symmetric systems having *R*=*eR* with good agreement. That is,

$$\frac{\alpha \cdot \delta_N}{\delta_E \cdot R} \approx \frac{\alpha \cdot \delta_{Nperi}}{\delta_{Eperi} \cdot eR} \tag{8}$$

$$\delta_{NPeri} \approx \frac{\delta_{EPeri}}{\delta_E} \cdot \delta_N \qquad (\because eR = R) \tag{9}$$

The strength modification factor γ can be derived from this previous work's conclusion as follows,

$$\begin{aligned}\gamma &= \frac{eR_x}{R_{0x}} \\ &= \frac{1}{\dfrac{Q_{Lx}}{Q_{Px}} + \dfrac{\left|T_{Lx} + 0.5 \cdot T_{Ly}\right|}{T_{P\theta}}} \cdot \frac{Q_{Lx}}{Q_{Px}} \\ &= \frac{1}{1 + R_{Sx}}\end{aligned} \tag{10}$$

$$R_{Sx} = \frac{\left| f_y + 0.5 \cdot f_x \right|}{T_{P\theta}} \cdot Q_{Px} \tag{11}$$

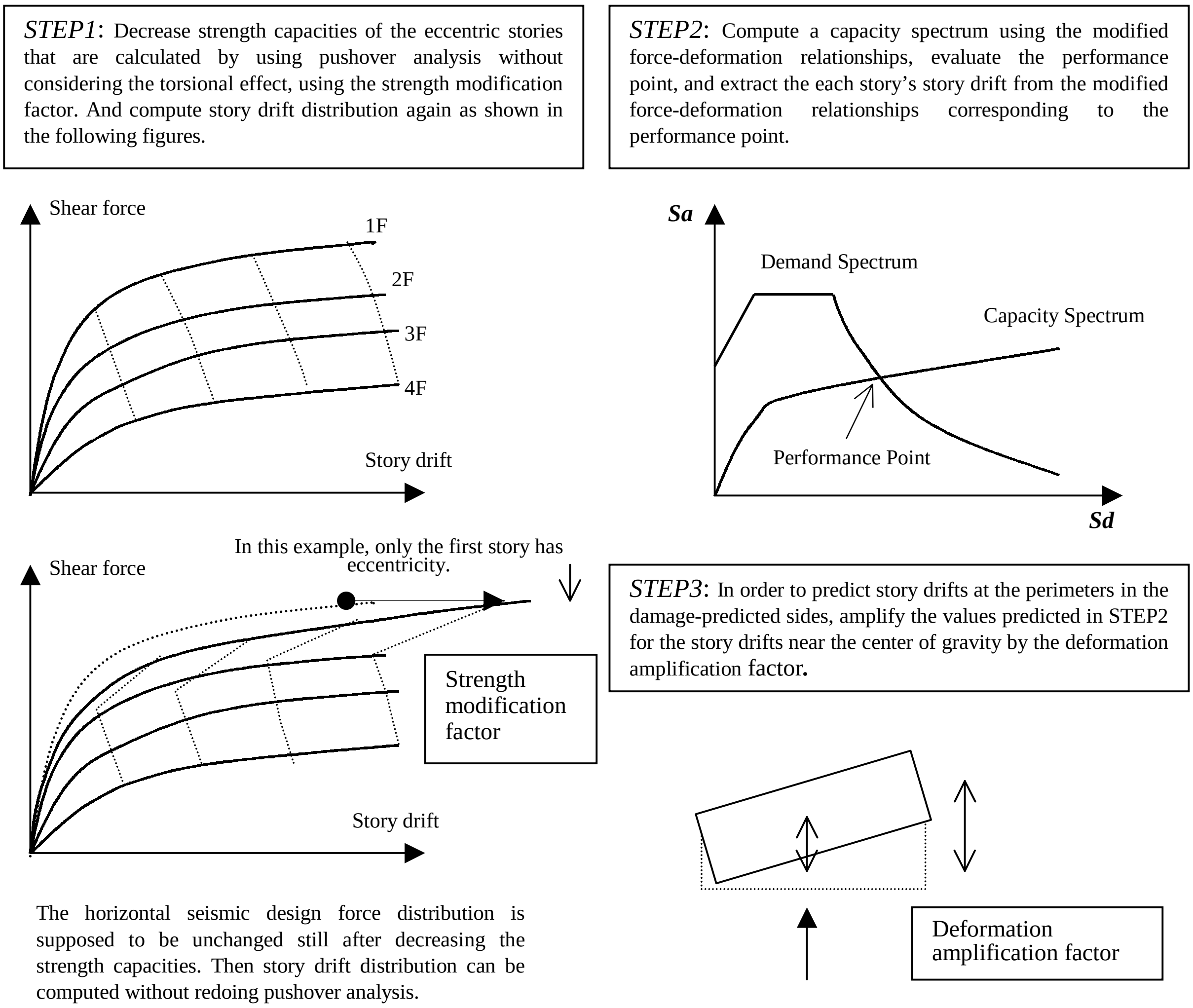


Figure 3: The procedure for seismic performance estimation of asymmetric

in which R_{0x}=the shear strength capacity ratio of asymmetric systems in the x-direction calculated without considering the torsional effect; R_{Sx}=the strength eccentricity coefficient.

And the deformation amplification factor β can be derived from Equation (9) as follows,

$$\beta = \delta_{Eperi} / \delta_E \tag{12}$$

This factor β can be calculated by using a linear and static three-dimensional analysis method, which is not complicated.

The outline of the procedure for seismic performance estimation of asymmetric buildings using these factors is shown in Figure 3.

PREDICTION OF INELASTIC RESPONSES OF ASYMMETRIC BUILDING'S MODELS

In order to verify the proposed procedure, parametric studies for inelastic responses of the 3-story asymmetric building's models are carried out.

The following assumptions are used for the earthquake response analyses of the systems.

(1) Each system has a rigid floor diaphragm and each foundation is fixed on the ground.

(2) Horizontal rigidity and strength of each lateral force-resisting element arranged in the x-and y-directions are independent in each direction. Torsional rigidity and torsional strength of each lateral force-resisting element are neglected.

(3) The force-deformation relationship of each resisting element is assumed to be bilinear with sufficient

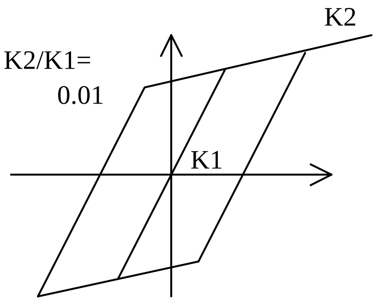


Figure 4: Bi-linear type

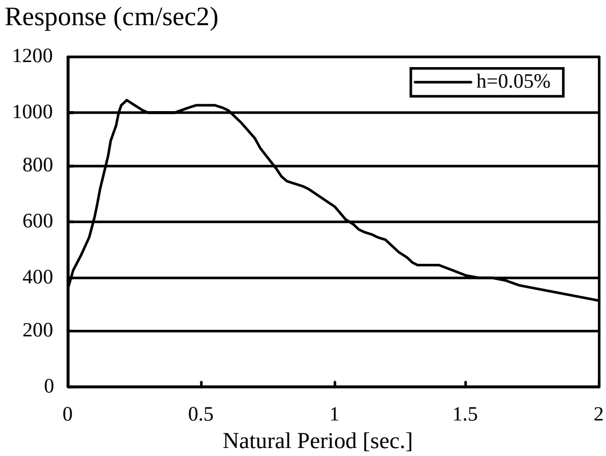


Figure 5: Linear response spectrum

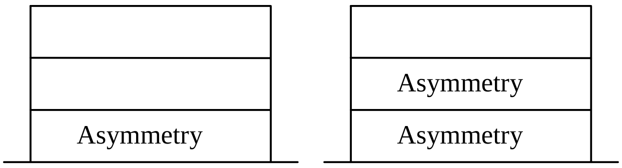
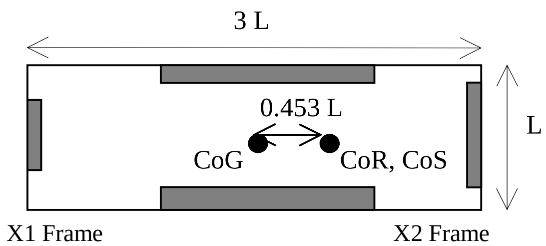
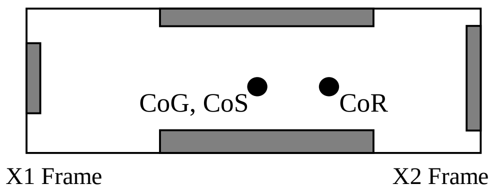


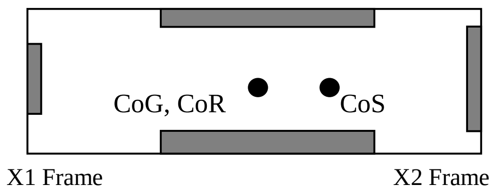
Figure 6: Stories with plan asymmetry



(a) Rigidity-strength eccentric type



(b)Rigidity Eccentric type



(c) Strength eccentric type

CoG: Center of gravity
CoR: Center of rigidity
CoS: Center of strength

Figure 7: Plans of the asymmetric story

ductility as shown in Figure 4.

Table.1 Parameters of building's models

Model name	Story with plan asymmetry	Eccentric Type	Strength modification factors	Deformation amplification factors
I	The 1st	Rigidity-strength eccentric	0.77	1.38
II	The 1st	Rigidity eccentric	1.00	1.38
III	The 1st	Strength eccentric	0.77	1.00
IV	The 1st and the 2nd	Rigidity-strength eccentric	0.77	1.38

(4) Vertical and torsional components of the earthquake ground motions are neglected. The earthquake lateral ground motion is inputted the systems in one direction, in which systems have eccentricities.

For the response analysis, a step-by-step time integration method (linear acceleration method) is used. Damping is assumed to be proportional to the initial stiffness with 5 % damping ratio for the first mode of vibration and for all the response processes after yielding.
The input ground motion is an artificial ground motion with random path of which the maximum acceleration and velocity are 355.7 cm/s/s and 57.4 cm/s, respectively. The linear response spectrum for 1-DoF systems with damping ratio h=0.05 is shown in Figure 5.

The building's models have one or two asymmetric-plan stories as shown in Figure 6. The asymmetric plans are classified into the rigidity-strength eccentric type, the rigidity eccentric type or the strength eccentric type as shown in Figure 7. Story's rigidity distribution and story's shear strength capacity distribution are both proportional to the lateral shear distribution factor *Ai* defined by Equation (13), which is regulated in Japanese building code.

$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i \right) \cdot \frac{2T}{1+3T} \tag{13}$$

in which $\alpha_i = W/Wn$; W=weight above i-th story; Wn=weight above ground level; T=fundamental natural period (sec.).
The fundamental natural uncoupled-lateral period of all models is 0.3sec. And the ratio of a shear strength capacity of the first story to weight above ground level of all models is 0.4. Parameters of each building's models are listed in Table.1.

The prediction method for inelastic story drifts of the asymmetry building's models, which simulate the procedure shown in Figure 3, is organised in the following phases;

1) Compute the amplification factor β by using Equation (12) based on a linear and static three-dimensional analysis.
2) Compute the force-deformation relationship of each story's each frame by two-dimensional pushover analysis. Horizontal seismic forces used in pushover analysis are determined according to the *Ai* shear distribution factor.
3) Compute the strength eccentricity coefficient according to Equation (11) using the shear strength capacity of each story's each frame. And compute the strength modification factor γ.
4) Decrease the shear strength capacities of the asymmetric-plan stories using the strength modification factor γ.
5) Using the modified force-deformation relationships, compute the capacity spectrum by using Equations (1), (2) and (3).
6) Prepare the equivalent 1-DoF system, which has the skeleton curve simulating the capacity curve. And compute the inelastic deformation of this model using a step-by-step time integration method.
7) Regard the inelastic deformation of the equivalent 1-DoF system as the performance point of asymmetric building's model. And seek for the analysis step-number n of the pushover analysis corresponding to the performance point.
8) Extract the each story's output by pushover analysis at the n-th step. The output is regarded as the value predicted for the story drift near the center of gravity (CoG) of each story.

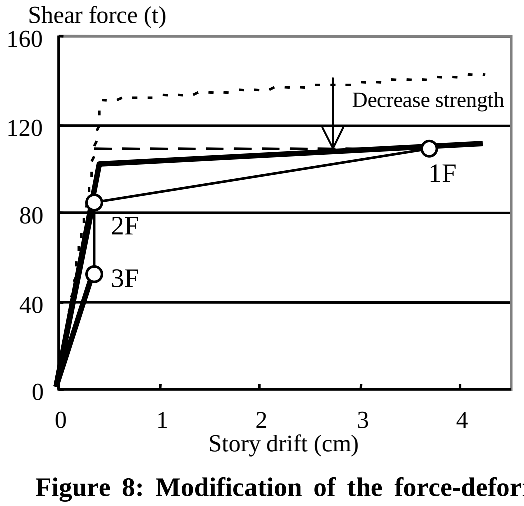


Figure 8: Modification of the force-deformation relationship for the model-I

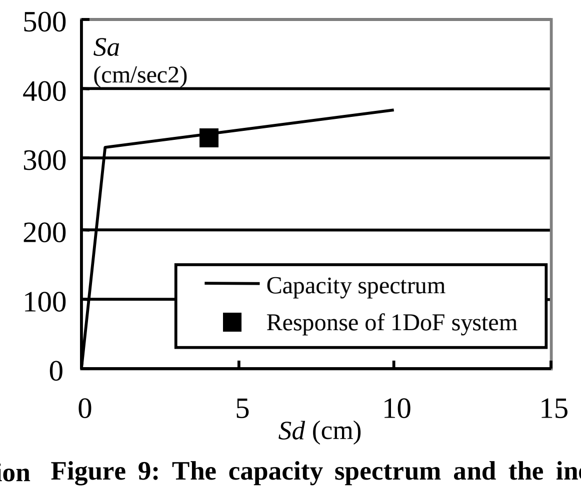


Figure 9: The capacity spectrum and the inelastic deformation of the equivalent 1-DoF system for the model-I

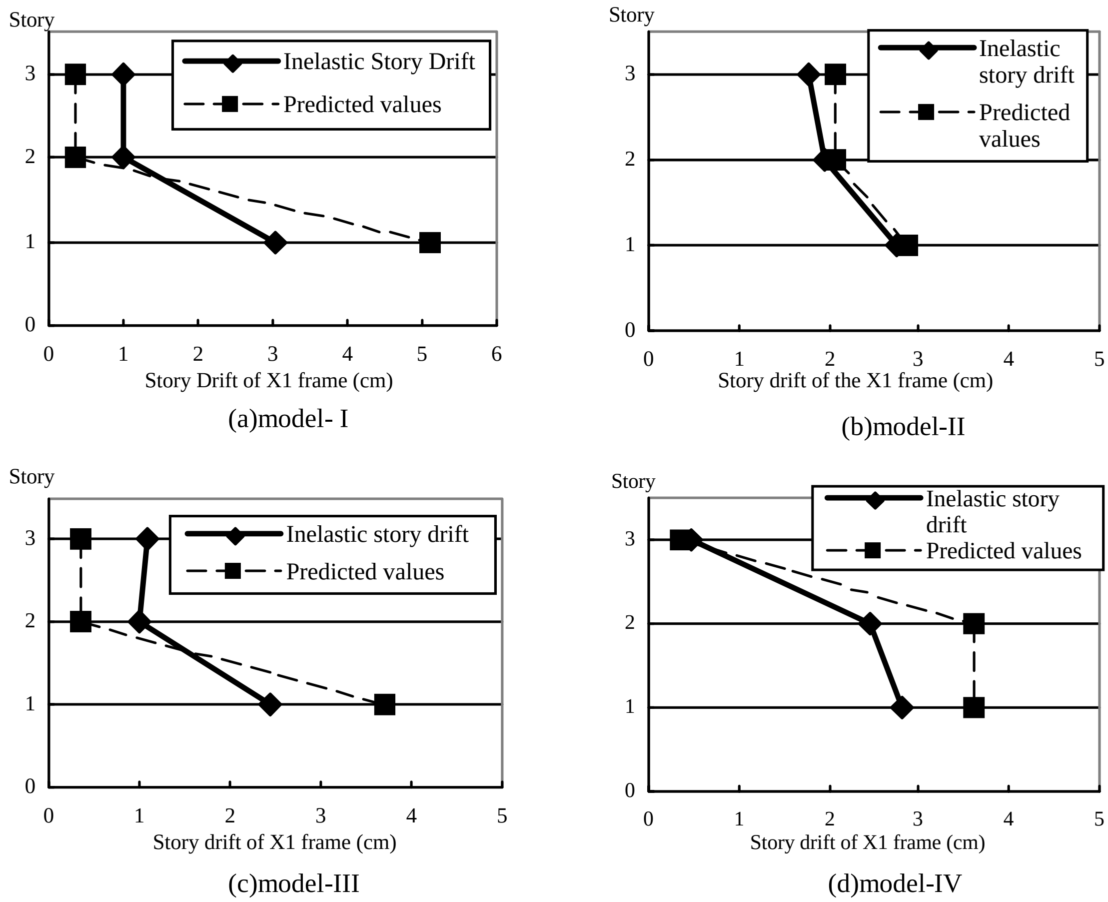


Figure 10: Prediction of inelastic story drifts at the perimeters in the damage-predicted sides

9) Amplify the each story's output extracted in phase 8) by the amplification factor. The amplified output is regarded as the value predicted for the story drift at the perimeter in the damage-predicted side of each story.

In practice, the performance point is given as the intersection between the capacity spectrum and the demand spectrum. However, in the method, the performance point is given as the inelastic deformation of the equivalent 1-DoF system. Figure 8 shows the modified force-deformation relationships of the model-I. The dotted line showing the force-deformation relationship of the asymmetric-plan story computed without considering the torsional effect is degraded to the solid line by using the strength modification factor. Figure 9 shows the capacity spectrum and the inelastic deformation of the equivalent 1-DoF system. The each story's drift near the CoG is predicted by extracting the story drift from the modified relationships, corresponding to the inelastic deformation of the equivalent 1-DoF system as shown in Figure 9. Furthermore, these values are multiplied by the amplification factor β.

Figure 10 shows inelastic story drifts at the perimeters in the damage-predicted sides of each building's model predicted by the above-mentioned method, comparing with those computed by a step-by-step time integration method. It is cleared that inelastic story drifts of asymmetric-plan stories can be predicted conservatively and approximately by the proposed procedure. However, comparatively large errors in the prediction are recognized for the models except the model-II. Thus, the supplementary analyses are carried out to examine the source of the errors. The analysis for the model-I is summarized in Figure 11. In the supplementary analysis, the each story's drift near the CoG is obtained by analyzing directory the responses of the corresponding 3-story symmetric system using a step-by-step time integration method without converting the 3-story system to the equivalent 1 DoF system. Figure 12 shows the outputs of the analyses for the model-I and the model-III. The predicted values in Figure 12 agree better with those computed by a step-by-step time integration method. It means that the torsional effect can be evaluated by using the strength modification factor and the deformation amplification factor. And it is considered that the prediction errors in the Figure 10 are likely to arise after converting the multi-story systems, which have the modified force-deformation relationship into the equivalent 1-DoF systems.

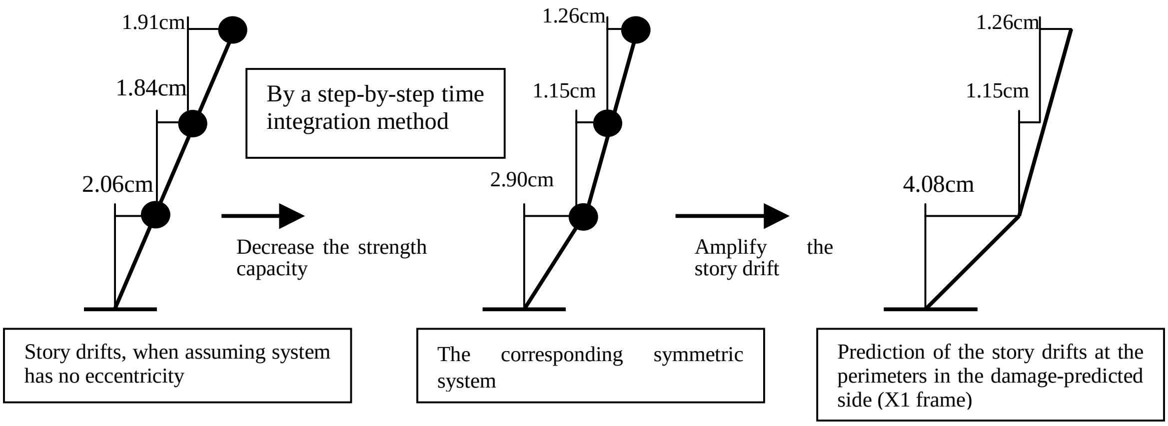


Figure 11: Supplementary analysis for the model-I

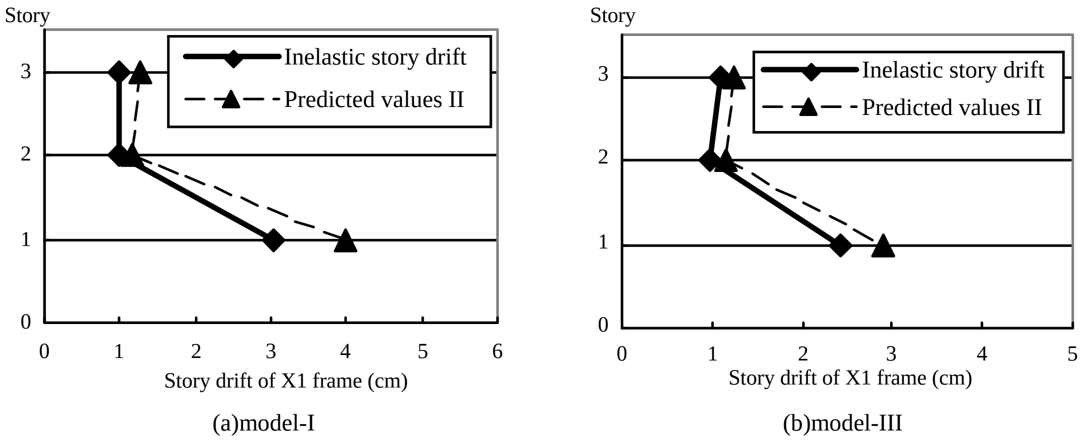


Figure 12: Prediction of inelastic story drifts at the perimeters in the damage-predicted sides (II)

CONCLUSION

1) In order to evaluate the torsional effect to inelastic seismic responses of asymmetric buildings, the strength modification factor and the deformation amplification factor were introduced. And using these factors, the procedure for seismic performance estimation of asymmetric buildings was presented.
2) The proposed procedure was examined by parametric studies for inelastic responses of three-story asymmetric building's models with some types of asymmetric-plan stories. From the results, it was cleared that the torsional effect can be evaluated by using the two introduced factors, and the story drifts at the perimeters in the damage-predicted sides of asymmetric-plan stories can be predicted conservatively and approximately by the proposed procedure.

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