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A method to estimate the behavior of high-rise RC frame buildings during earthquakes

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ABSTRACT : For the evaluation of the dynamic structural behavior, this paper proposes a simple method to estimate the nonlinear response values using the "constant displacement rule", for high-rise buildings. Story displacement responses are calculated using elastic response spectra, elastic stiffness eigen modes, and the SRSS method. Story shear forces and over turning moments are obtained using a nonlinear load - displacement relationship of the substructures.

The values obtained by this method agreed well with the values obtained from frame type dynamic response analyses.

1. INTRODUCTION

In Japan, the reinforced concrete rigid frame structures that exceed thirty stories have all been built recently. The key point to earthquake resistant design is the well-balanced consideration of three important factors; i) input ground motions, ii) dynamic structural behavior, iii) strength and ductility of the structural members. For the evaluation of the second factor, this paper proposes a simple method to estimate the nonlinear response values using the "constant displacement rule", for high-rise buildings.

Since we can adopt the "constant displacement rule" to a structure that has a long natural period, like a high-rise building (Penzien 1960), we can estimate the elasto-plastic seismic response without using an equivalent linearization technique. In this paper, SRSS (Square Root of Sum of Squares) is used to calculate the story response displacement and the "constant story displacement rule" is verified by comparing these values with the dynamic frame analysis results. We calculate the story shear force corresponding to the story displacement with a nonlinear load - displacement relationship. The values are compared with the dynamic frame analysis results and the validity of the present method is confirmed.

2. ESTIMATING RESPONSE

2.1 Analysis model

A flow chart of the present method is shown in Figure 1. We idealize the structure by means of a bending and shear system model with a concentrated mass system, with each layer as one mass, as shown in Figure 2. Figure 3 shows how to calculate the elastic shear stiffness and the total elastic bending stiffness of each story. The summation of the

product of a_{ci}, E_c and x_i^2 for the total number of columns in each story is assumed to be the total elastic bending stiffness of each story.

where, a_{ci} : cross-sectional area of column

E_c : Young's modulus of cross-sectional area of column

x_i : distance from center of gravity in each story

Take ⊢ type and ＋ type substructures which have a span and a half of the story height in each layer (full story height only for first story) and calculated the shear force - story shear displacement relationship between each substructure. Calculate the story shear force - story shear displacement relationship by summing the values of each substructure. The elastic shear stiffness was calculated simultaneously. Apply the bending elastic stiffness and the shear elastic stiffness to the analysis model shown in figure 2, and perform eigen value analysis to estimate the seismic response of the structure.

2.2 Setting up velocity response spectra

Table 1 shows the smoothing velocity response spectrum S_v with a 2% damping factor from six different seismic motions used in the present method. Figure 4 shows the velocity response spectra with 2 % damping factor and smoothing spectrum, for the six seismic motions.

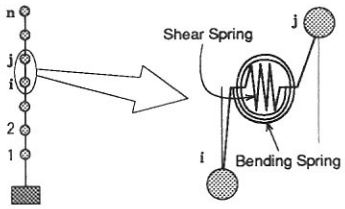


Figure 2 Idealized Model

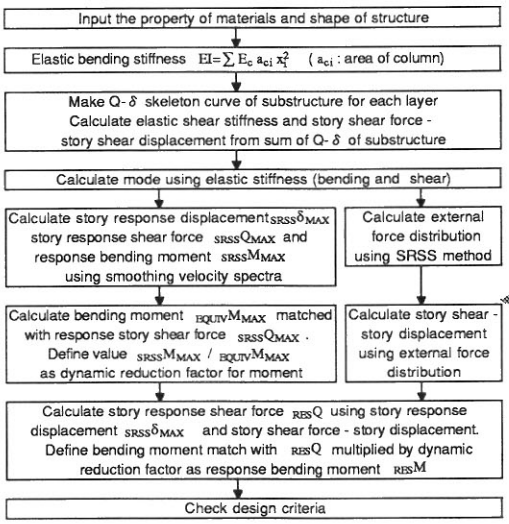


Figure 1 Flow Chart of Method

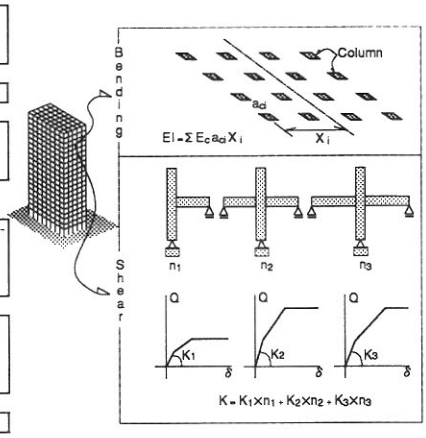
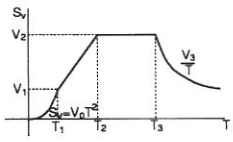


Figure 3 How to Calculate Elastic Stiffness

Table 1 Velocity Response Spectrum

	T1	T2	T3	V0	V1	V2	V3
El Centro NS	0.12	0.57	2.08	2399	34.5	164	341
El Centro EW	0.22	0.77	3.52	768	37.2	130	458
Taft NS	0.16	0.53	3.53	1715	43.9	145	513
Taft EW	0.17	0.51	2.67	1562	45.2	135	362
Hachinohe NS	0.20	0.74	2.63	954	38.2	141	371
Hachinohe EW	0.30	0.93	2.53	595	53.5	166	420

unit : cm, sec



2.3 Relationship between story shear force and story displacement

The story shear force - story shear displacement relationships calculated from the substructures, become the same, if the properties of the members, shape of the substructures etc. are the same. However, a resistance force is distributed in top and bottom of each layer corresponding to the external force, and thus the resistance force distribution corresponds to the external force distribution. The story shear force - story displacement relationship is calculated using the following procedure.

1) External force distribution is calculated by SRSS method for eigen value analysis.
2) Overturning moment (M_{ove}) at base of first floor column is calculated by means of yield story shear force calculated using substructures.
3) External force which makes M_{ove} is calculated from shape of distribution in 1).
4) Force calculated from this external force assumed to be the yield story shear force.
5) Yield story shear displacement δy moves on the "δy line". "δy line" connects the points of yield displacement.
6) Story displacements are calculated by adding total bending displacements to story shear displacements.

In order to distribute the yield story shear force in the upper and lower layers with this procedure, it is assumed that the columns do not yield.

2.4 Estimating response

1) The story displacements, story shear forces and bending moments from the first to the fifth degree are calculated by eigen value analysis using the analysis model in *2.1*, and the velocity response spectra set up in *2.2*.
2) The SRSS method was used for the value of each degree and to calculate the elastic response values of the story displacement, story shear force ${}_{SRSS}Q_{MAX}$ and bending moment ${}_{SRSS}M_{MAX}$. The bending moment distribution ${}_{EQUIV}M_{MAX}$ was calculated to match with ${}_{SRSS}Q_{MAX}$, and considering ${}_{SRSS}M_{MAX}$ / ${}_{EQUIV}M_{MAX}$ as a dynamic reduction factor in the bending moment.

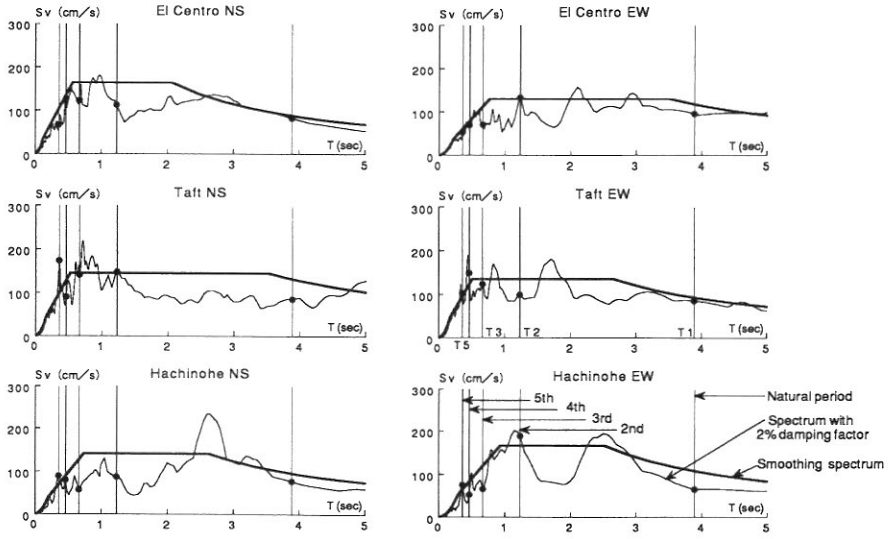


Figure 4 Velocity Response Spectra

3) In high-rise buildings, we consider that the "constant displacement rule" can be adopted, and an elastic story displacement is regarded as an elasto-plastic response value.
4) The story response shear force $_{RES}Q$ applying to the story displacement was calculated with the story shear force - story displacement relationship.
5) The bending moment was calculated to match with $_{RES}Q$, and the product of the dynamic reduction factor and this bending moment gives the response bending moment, and a change of axial force in the outside columns.
6) The distribution of story displacement and story shear force were examined, and the ductility factor, change of axial force etc. satisfied the design criteria.

3. APPLICATION OF PRESENT METHOD TO A 60 STORY REINFORCED CONCRETE RIGID FRAME STRUCTURE

The results from applying this method to a 60 story reinforced concrete rigid frame structure (Figure 5) (Yamamoto and Yoshimura 1990) are described below.

3.1 Total elastic bending stiffness and elastic shear stiffness

Figure 6 compares the total elastic bending stiffness calculated using this method with the exact values. The left side shows the total elastic bending stiffness, while the right side gives the ratio. Both values agree well except for at the top. This is not thought to be a problem because the differences in the bending stiffness in the upper stories has little influence on the response. The story shear force - story shear displacement relationship calculated using the substructure is shown in Figure 7. Figure 8 shows the elastic shear stiffness calculated from Figure 7 with

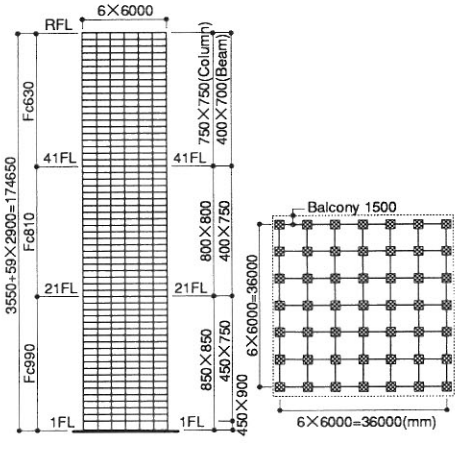


Figure 5 A 60 Story RC Building

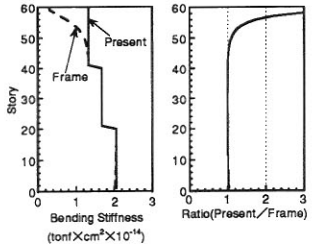


Figure 6 Whole Elastic Bending Stiffness

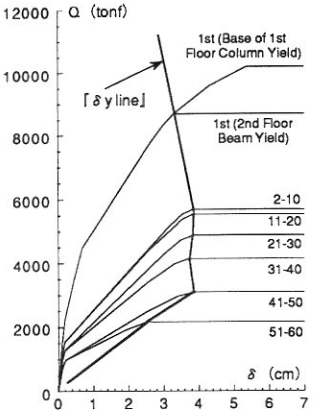


Figure 7 Story Shear Force - Story Shear Displacement Relationship

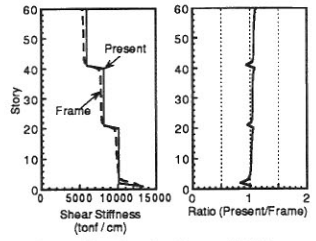


Figure 8 Elastic Shear Stiffness

the results from the static frame analysis. The left side shows the elastic shear stiffness, while the right side gives the ratio. Both values agree well. It may be understood from the above that the elastic stiffness of a structure can be estimated sufficiently, with the simple analysis used in this method.

3.2 Relationship between story shear force and story displacement

Figure 9 shows the story shear force - story displacement relationship calculated with the method in 2.3 using the yield story shear force. Figure 10 shows the static incremental analysis results for a frame with mode superposition external force distribution. Compared with static frame incremental analysis, the displacement of yield calculated with the present method is slightly larger in the lower stories. However, both results show good correspondence.

3.3 Story response displacement

Figure 11 shows the story response displacements calculated using both the present method with dynamic frame analysis results. In the same figure, the results from a dynamic mass system analysis using the story shear force - story displacement relationship, calculated by the present method (Figure 9), is also shown.

The story response displacement using the present method is large compared to the story response displacement using the dynamic analyses, except in the lower stories when applying the El Centro EW and Taft EW seismic motions. Where the response is large when using these seismic motions in a structure, it may be considered that the bending stiffness of building is almost elastic, being mainly an axial stiffness in the columns and that nonlinearity appears only in shear displacement. Nonlinearity appears strongly with increasing displacement in the lower stories where the rate of shear displacement is large. Using elastic stiffness in the present method, it is difficult to express this phenomenon of increased displacements in the lower stories.

On the whole, it may be seen that the maximum story response displacement may be calculated using the present method, within the precision of the scatter of the seismic motions input.

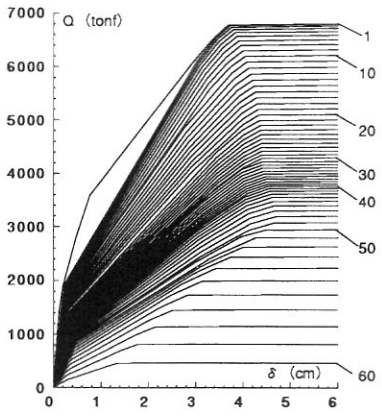


Figure 9 Story Shear Force- Story Displacement Relationship (Present Method)

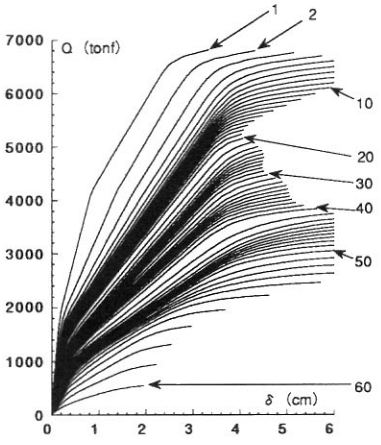


Figure 10 Story Shear Force- Story Displacement Relationship (Static Frame Analysis)

3.4 Story response shear force

The story response shear forces calculated using the present method and dynamic analyses are shown in Figure 12. The overall tendencies are similar to the story response displacements in *3.3*. Namely, except for the lower stories for El Centro EW and Taft EW, the story response shear forces using the present method show good agreement with those calculated from the dynamic mass system and dynamic frame analyses.

The story response shear forces may be evaluated in advance using this present method.

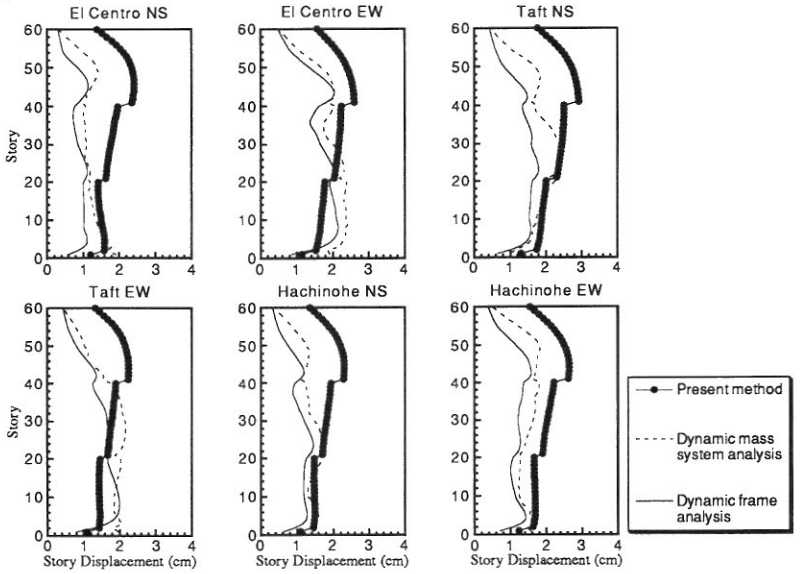


Figure 11 Story Response Displacement

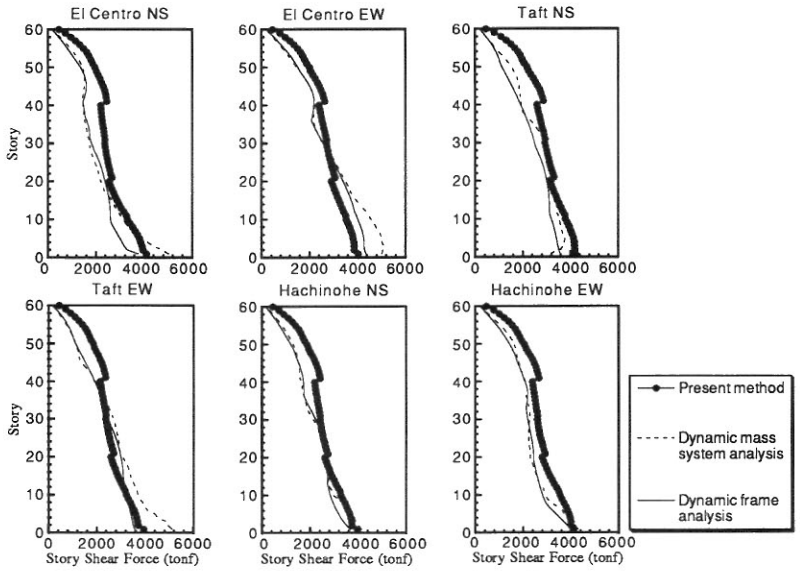


Figure 12 Story Response Shear Force

3.5 Change of axial force

The bending moments matched with the maximum story response shear forces were calculated in *3.4*. These values multiplied by the dynamic reduction factor ${}_{SRSS}M_{MAX}$ / ${}_{EQUIV}M_{MAX}$ gives the bending moment ${}_{RES}M$, where,

${}_{SRSS}M_{MAX}$: Maximum response bending moment calculated using SRSS method

${}_{EQUIV}M_{MAX}$: Bending moment matched with the maximum story response shear force ${}_{SRSS}M_{MAX}$ calculated using SRSS method.

As stated previously, because the whole bending stiffness is thought to be elastic during response, the change in the axial force in the outside columns from ${}_{RES}M$ using whole elastic bending stiffness may be calculated. We compare a change of axial force in outside column calculated using a present method with those from dynamic analyses in figure 13.

The results from the present method show a good correspondence with those from the dynamic analyses, but are slightly smaller in the lower stories for Taft EW case. The results for Taft EW where $h = 0.02 \times T_1 / T_i$ which modified the velocity response spectra multiplied by a correction factor for h are shown in Figure 14. In this case, the change of axial force in the lower stories becomes larger than the values calculated with h constant, and they approximate the values obtained form the dynamic analyses. Figure 15 shows the contribution rate of the story shear force at each degree with the SRSS method. The value of the square of the story shear force at each degree divided by the sum of the squares of the story shear forces is defined as the contribution rate. Where h is constant, the influence of a higher degree modes is large compared with where $h = 0.02 \times T_1 / T_i$. The dynamic reduction factor where h is constant is calculated by elastic story displacement with a large influence due to the higher degree. Because we calculated the elasto-plastic story shear force using the story displacements and each story's $Q - \delta$ skeleton curve with the present method, and the displacement spectrum is so small with the higher degree, it can be understood that the influence of the higher degree is small. Where h is constant, it is possible that we evaluated the change of axial force to be too small, because the overturning moment calculated from the elasto-plastic story shear

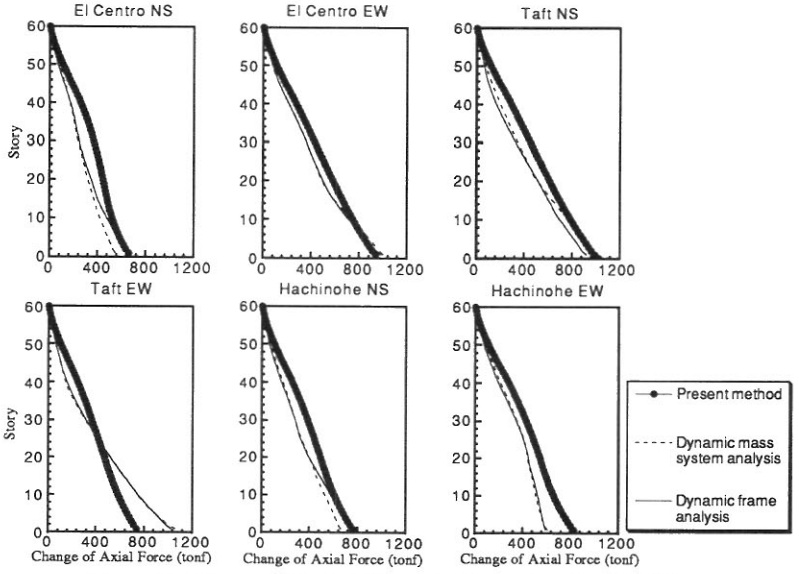


Figure 13 Change of The Axial Force in The 1st floor Outside Column

force which is influenced by the higher degree multiplied by the dynamic reduction factor calculated from the elastic story shear force is influenced by the higher degree, and changes the axial force. This phenomenon is improved by using a dynamic reduction factor calculated from the elastic story shear force which is influenced by the higher degree where $h = 0.02 \times T_1 / T_i$. When using a smoothing response spectrum that envelops the response spectrum like in the present method with a constant damping factor h, safe values are obtained when calculating the story response displacement and the story response shear force. However when the change of axial force is calculated, there is some possibility that unsafe values are obtained having included the influence of the higher degree mode in the dynamic reduction factor.

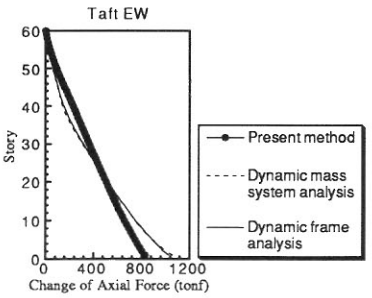


Figure 14 Change of Axial Force in Outside Column (Taft EW) (using $h=0.02 \times T_1/T_i$)

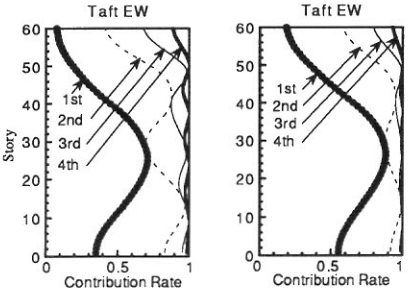


Figure 15 Contribution Rate of Story Shear Force with SRSS method

4. CONCLUSION

A simple method to estimate the response of a high-rise reinforced concrete rigid frame structure using the SRSS method was proposed, and applied to a 60 story reinforced concrete rigid frame structure, and the following points were obtained.

1) Precision in estimation using the present method may be compared with the scatter made by the input seismic motions.
2) You can estimate the response in the early stages of design using the present method, and you can predict the design criteria in advance.
3) The present method is useful in ensuring the seismic response of a rigid frame structure.
4) Where an elastic shear force is calculated using SRSS with acceleration response spectra, there is a possibility that the influence of the higher degree mode may be excessively included in it.

ACKNOWLEDGMENTS

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