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Efficient seismic analysis of multi-story buildings

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Abstract. The equivalent static force procedure and the response spectrum analysis method are widely used for seismic analyses of multi-story buildings. The equivalent static force procedure is one of the most simple but less accurate method in predicting possible seismic response of a structure. The response spectrum analysis method provides more accurate results while it takes much longer computational time.

In the response spectrum method, dynamic response of a multi-story building is obtained by combining modal responses through a proper procedure such as SRSS or CQC method. Since all of the analysis results are expressed in absolute values, structural engineers have difficulties to combine them with the results obtained from the static analysis. Design automation is interrupted at this stage because of the difficulty in the decision of the most critical design load.

Pseudo-dynamic analysis method proposed in this study provides more accurate seismic analysis results than those of the equivalent static force procedure since the dynamic characteristics of a structure is considered. And the proposed method has an advantage in combination of the analysis results due to gravity loads and seismic loads since the direction of the forces can be considered.

Key words: seismic analysis; equivalent static force procedure; response spectrum analysis method; pseudo-dynamic analysis method; lateral seismic force; story shear force; multi-story building.

1. Introduction

All kinds of possible load cases should be considered in proper combinations for earthquake resistant design of a building structure. Structural analysis of a building due to dead load, live load, and wind load can be performed through a static analysis procedure. However, in some cases, static analysis does not give satisfactory results for seismic analysis of a building.

A building structure is expected to experience significant inelastic deformations when subjected to a strong ground motion. However, in general, linear analysis is performed for practical earthquake resistant design of a building structure. The effect of the inelastic response of the structure is accounted for using the design response spectrum which accounts for the factors such as ductility and damping effect. Most of the seismic codes suggest to use elastic analysis procedure for seismic analysis of a multi-story building structure. However, in some countries such as Japan and New Zealand, the design concepts are based on the ultimate lateral load resistance

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after the deformation of a plastic mechanism.

The equivalent static force procedure has been widely used for seismic analysis of small buildings taking the advantage of its simplicity in procedure. However, the results obtained from this method may have lack of accuracy when the structure is a high-rise building or has significant irregularity in plan or elevation. Therefore, this procedure is supposed to provide fairly conservative results. Even though the procedures of the response spectrum analysis method is more complicated than those of the equivalent static force procedure, its analysis results are more accurate. Normally, the equivalent static force procedure is used for the analysis of regular low-rise buildings and the response spectrum analysis method has been used for the analysis of high-rise buildings or irregular structures.

In most cases, the results from the response spectrum analysis are expressed in absolute values through SRSS(Square Root of the Sum of the Squares) or CQC(Complete Quadratic Combination) method in combining the dynamic responses obtained for each mode of vibration. Structural engineers should combine the results obtained from response spectrum analysis and those of static analysis due to dead load and live load, which has positive or negative values. Therefore, the selection of the most critical design load case for each member is difficult and experienced engineer's judgement is required. This is one of the reason why the response spectrum analysis has not been commonly used for an earthquake resistant design of a building and computerized design automation of a building is interrupted.

The basic concept of a pseudo-dynamic analysis method, proposed in this study, is that the member forces are mainly governed by the story shear force. The proposed method provides seismic analysis results which can directly be combined with the results obtained from static analysis. Also the results obtained from the proposed method are very close to those from the response spectrum analysis since appropriate vibration characteristics are considered in analysis.

2. Seismic analysis methods and shortcomings of response spectrum analysis

It is specified that "All buildings and portions thereof shall be designed and constructed to sustain all dead loads and all other loads specified in the code."(UBC 1991). Seismic analysis methods for an earthquake resistant design of multi-story buildings can be classified into three types; equivalent static force procedure, response spectrum analysis method and time history analysis method.

2.1. Seismic analysis methods

The equivalent static force procedure is derived basically for the convenience of engineers by approximating the response of a structure. But this method involves some critical assumptions such as the dynamic response of a structure is mainly governed by the first mode of the vibration and the structural shape is regular. However, this procedure is not appropriate for analysis of an irregular or high-rise building because the dynamic response of the structure is not properly considered.

Response spectrum analysis method and time history analysis method have been used for more accurate seismic analysis. The main objective of a seismic analysis is in getting the maximum responses of a structure due to an earthquake load. Response spectrum analysis is one of the most effective dynamic analysis methods in accomplishing this objective.

Since the response spectrum analysis method considers the reasonable vibrational periods and mode shapes of a structure, analysis provides quite accurate results even for irregular or high-rise building structures. However, the final responses of a building are always expressed in absolute values because either SRSS or CQC method is used in combining modal responses of a structure in the process of combination.

2.2. Shortcomings of response spectrum analysis

In this method, final responses are expressed in absolute values through combination of modal responses. It seems reasonable because the structural response under earthquake effect may have both positive and negative values of similar amount when it vibrates. It may not cause any problem when the maximum force occurring at a certain structural member is of interest.

However, seismic response is not used alone but used in combination with the results of static analysis for dead loads and live loads. When earthquake loads are included in the design of a structure, two types of load combinations are provided in ACI 318-89 as follows;

$$U=1.05D+1.28L+1.40E \tag{1}$$

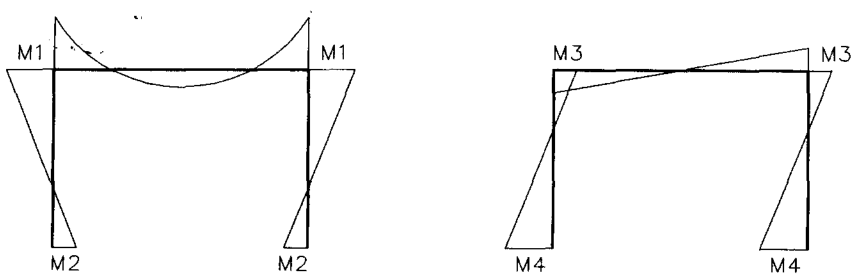
$$U=0.90D+1.43E \tag{2}$$

Analysis results obtained from static analysis have either positive or negative sign while those obtained from response spectrum analysis are expressed always in absolute values. This may cause difficulties in combining both results to select the most critical load case for design of a structural member.

2.2.1. Problems in bending moment combination

The bending moment diagram of a single story structure under gravity loads can be obtained as shown in Fig. 1(a). Equivalent static force procedure of the same structure under earthquake loads will provide the bending moment diagram as shown in Fig. 1(b). Design of the column on the right hand side will be accomplished by the simple summation of bending moments obtained from two different analysis stage such as shown in Fig. 2.

However, the direction of bending moments occurring in each column can not be defined



(a) Gravity load (b) Seismic load

Fig. 1 Bending moment diagram for gravity and seismic loads.

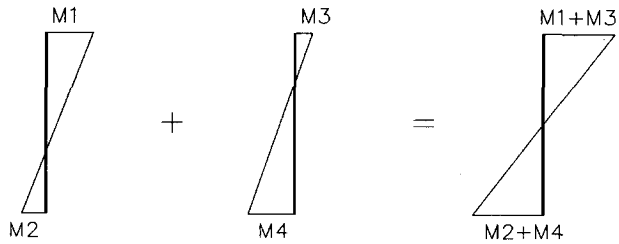


Fig. 2 Superposition of bending moments in a column for gravity and seismic loads.

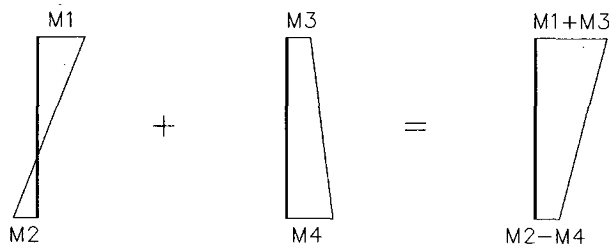


Fig. 3 Alternative superposition of bending moments in a column.

when response spectrum analysis method is employed. Normally, the coefficient C_m in Eq. (3) is used in the design of column to consider the moment distribution along the axis. If we establish the direction of bending moments due to seismic load as shown in Fig. 3, the more critical load case can be obtained with the value of C_m larger than the previous case.

$$C_m = 0.6 - 0.4\left(\frac{M_1}{M_2}\right) \tag{3}$$

However, it is not acceptable that the bending moment as shown in Fig. 3 will occur during an earthquake. Accordingly, too much design load will be applied in some cases if we design a structural member due to the most critical load case which is not realistic.

2.2.2. Problems in combination of axial forces and bending moments

The axial force and the bending moment are the most important factors in the design of a reinforced concrete column. In general, the relationship between bending moment and axial force which can be resisted by a column could be expressed as shown in Fig. 4. The bending moment capacity increases as the axial compression in a column decreases in the region of compression failure. On the other hand, the larger bending moment can be resisted as the axial compression increases in the region of tension failure. Therefore, it can not be clarified whether the most critical design load case will be the summation or the subtraction of bending moments when the axial force is constant.

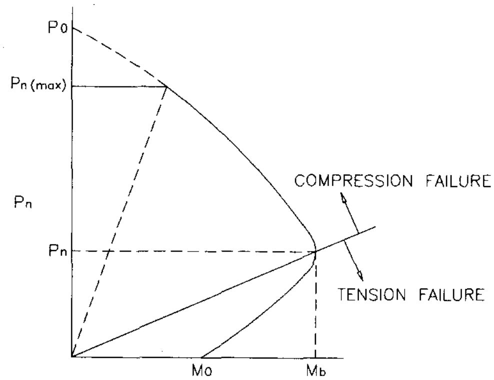


Fig. 4 Design load-moment strength interaction diagram.

3. Development of pseudo-dynamic analysis method

The pseudo-dynamic analysis method proposed in this study can provide member forces with appropriate direction leading to the automation of structural design without an engineer's judgement. Moreover, the accuracy of analysis results obtained from the proposed method is very close to those of the response spectrum analysis method. The pseudo-dynamic analysis method calculates member forces in a static manner. The lateral seismic forces obtained using part of the response spectrum analysis procedure is employed to consider the appropriate vibration characteristics of a building structure. Thus, the results obtained from static analysis can easily be combined with the results of the pseudo-dynamic analysis which provides proper relationship between member forces. Therefore, structural design automation can be accomplished using this method.

3.1. Calculation of lateral seismic force and story shear force

It is well known that bending moments and shear forces in beams and columns of a multi-story building due to lateral forces mainly depend on the story shear force. This principle is used for the development of the portal method which is one of the most efficient method for analysis of a multi-story building subjected to lateral forces. Therefore, bending moments and shear forces in a member can be estimated through a simple procedure when the corresponding story shear force is known.

The cantilever method was derived based on this concept that the axial force in a column is governed by overturning moment. Since the overturning moment occurring at a story can be calculated by accumulating story shear force multiplied by the story height, it can be concluded that the axial force in a column is also governed by the story shear force. Therefore, member forces of a multi-story building subjected to lateral forces are directly related to story shear forces.

The same relationship is valid in the response spectrum analysis of a multi-story building structure. When the story shear force has been calculated for a certain mode of vibration, member forces can be approximated in proportion to the story shear force as shown in Eq. (4).

$$a_i = \alpha V_i \tag{4}$$

where, a_i represents bending moment or shear force in a beam or a column, α is a proportional constant relating V_i to a_i, and V_i is the corresponding story shear force for the i-th mode of vibration. Applying the relationship in Eq. (4) to all modes of vibration, a relationship shown in Eq. (5) can be obtained through SRSS procedure assuming the same proportional constant α for each mode of vibration.

$$A=\sqrt{\sum a_i^2}\simeq\sqrt{\sum(\alpha V_i)^2}=\alpha\sqrt{\sum V_i^2}=\alpha V \tag{5}$$

In Eq. (5), it can be noticed that the resultant member force, A, is also related to the resultant story shear force, V, in the same manner as in Eq. (4). Therefore, it can be possible to obtain member forces using static analysis procedure in the same accuracy as those of the response spectrum analysis method if the story shear forces are forced to be the same in both procedures.

The essential procedure in the proposed method is to find the equivalent static lateral forces that will result in the same story shear forces as those of the response spectrum analysis method. The procedures to calculate story shear forces are adopted from the response spectrum analysis method and the equivalent static lateral forces are obtained as the differences between adjacent story shear forces. Application of these lateral forces to a multi-story building structure will result in the member forces which are very close to those from the response spectrum analysis.

3.2. Pseudo-dynamic analysis procedure

The procedures of the pseudo-dynamic analysis method will be discussed in comparison with those of the equivalent static force procedure and the response spectrum analysis in this section. The flow of the equivalent static force procedure can be expressed as shown in Fig. 5. The natural period of a structure is obtained by a simple formula provided in the code. Lateral seismic forces are obtained by distributing the base shear force over the height of a structure. Corresponding member forces can be calculated using a static analysis procedure.

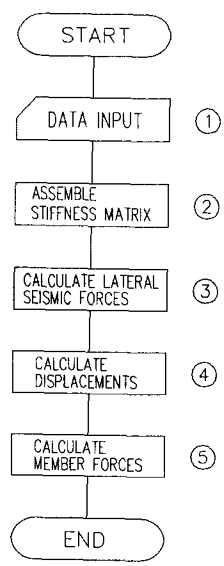


Fig. 5 Flow of equivalent static force procedure.

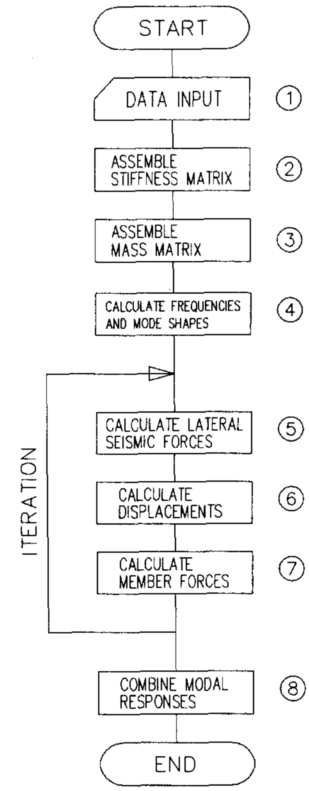


Fig. 6 Flow of response spectrum analysis.

The response spectrum analysis method is more complicated than the equivalent static force procedure as shown in Fig. 6. Dynamic characteristics of a structure such as the natural periods and mode shapes should be obtained to calculate the responses for each mode of vibration. Static lateral forces, displacements, and story shear forces per each mode of vibration are combined through SRSS or CQC procedure.

The first half of the pseudo-dynamic analysis is similar to the response spectrum analysis method while the rest of the procedure is the same as the equivalent static force procedure as shown in Fig. 7. Lateral seismic forces are calculated in the same manner as the ones used in the response spectrum analysis method. The story shear forces are calculated from lateral seismic forces and the iteration should be performed for all modes of vibration. Story shear forces for each mode of vibration are combined by the SRSS method as follows;

$$V=\sqrt{V_1^2+V_2^2+\cdots+V_n^2} \tag{6}$$

where, n is the number of vibrational modes to be included in analysis.

In general, the SRSS method given in Eq. (6) is used to combine the responses obtained for each mode of vibration. However, it is recommended to use the CQC method when vibrational periods of two adjacent modes are very close. The lateral seismic force, F_i, to be applied at story level is calculated as follows;

$$F_i=V_{i-1}-V_i \tag{7}$$

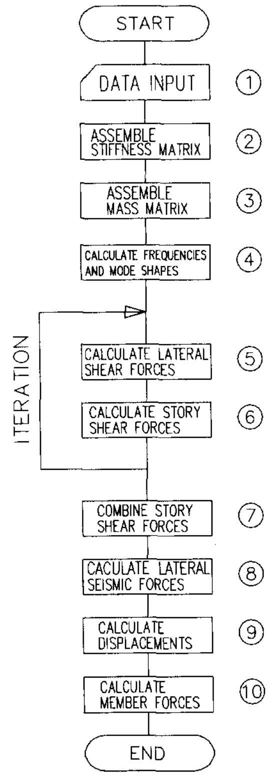


Fig. 7 Flow of pseudo-dynamic analysis.

where, V_i is the story shear force of the i-th story. Lateral shear forces are used in static analysis to obtain displacements and member forces.

The proposed pseudo-dynamic analysis method has advantages of the equivalent static force procedure and the response spectrum analysis method. The accuracy of the results are very close to those obtained from the response spectrum analysis method since the higher mode effect of vibration is considered in calculation of lateral seismic force. The proposed method considers appropriate direction of member forces which is directly related to the design of structural members.

4. Example multi-story buildings

The accuracy of the proposed pseudo-dynamic analysis method is verified using three types of multi-story building structures. Irregular framed structure and asymmetric structure were selected to examine the stiffness difference of a high-rise building and to consider the torsional effect of a building, respectively. Three different example buildings adopted for the verification of the proposed method are as follows;

1) Regular structure
2) Irregular structure with setback
3) Asymmetric structure

Table 1 Size of beams and columns for example structures (mm)

Story	Beam	Column
1-3	400×600	800×800
4-6	400×600	700×700
7-9	400×600	600×600
10-12	400×600	500×500
13-15	400×600	400×400

All of the buildings are 15 stories without underground floor as shown in Fig. 8. The story height of 3.5 meter was selected for all stories except the first floor which is 5.5 meter high. Typical live load for office buildings are used in the design of beams and columns as listed in Table 1. The thickness of the shear wall is 20 cm up to 6-th story, and the rest of the stories have 15 cm thickness.

The pseudo-dynamic analysis results for three types of multi-story building structures are compared to those obtained from the equivalent static force procedure and the response spectrum analysis method. Displacements and member forces, which are the most important factors in structural design, occurring at each story are compared. Results from the equivalent static force procedure and the pseudo-dynamic analysis are converted into absolute values for the purpose of comparison, because the response spectrum analysis provides displacements and member forces in absolute values. The response spectrum analysis can not account for the accidental torsion in a structure. Therefore, the effect of accidental torsion is not included in the equivalent static force procedure for comparison.

4.1. Regular structure

The regular framed structure used as an example 1 has the floor plan as shown in Fig. 8(a). Results obtained from three different seismic analysis methods are compared in Fig. 10. Bending moment at the end of the beams in the bay 2-3 are shown in Fig. 10. Bending moments and axial forces at the lower end of the column line 2 are shown in Figs. 10(b) and 10(c). Lateral displacements occurring at each floor are compared in Fig. 10(d).

As shown in Fig. 10(a), bending moments in the beams obtained from the pseudo-dynamic analysis are very close to those from the response spectrum analysis while the results from the equivalent static force procedure are overestimated by 30%. Bending moments at each column are in an excellent comparison to those of the response spectrum analysis method as shown in Fig. 10(b). However, slight difference in axial forces was observed in lower stories of the building.

It is required to limit the drift as well as the stress for an earthquake resistant design of high-rise buildings. As shown in Fig. 10(d), the displacements calculated from the pseudo-dynamic analysis method have little difference from those of the response spectrum analysis method in upper stories. Overestimation of displacements observed is not so significant that it may be negligible in design consideration.

4.2. Irregular structure with setback

In general, the equivalent static force procedure is not recommended for the seismic analysis

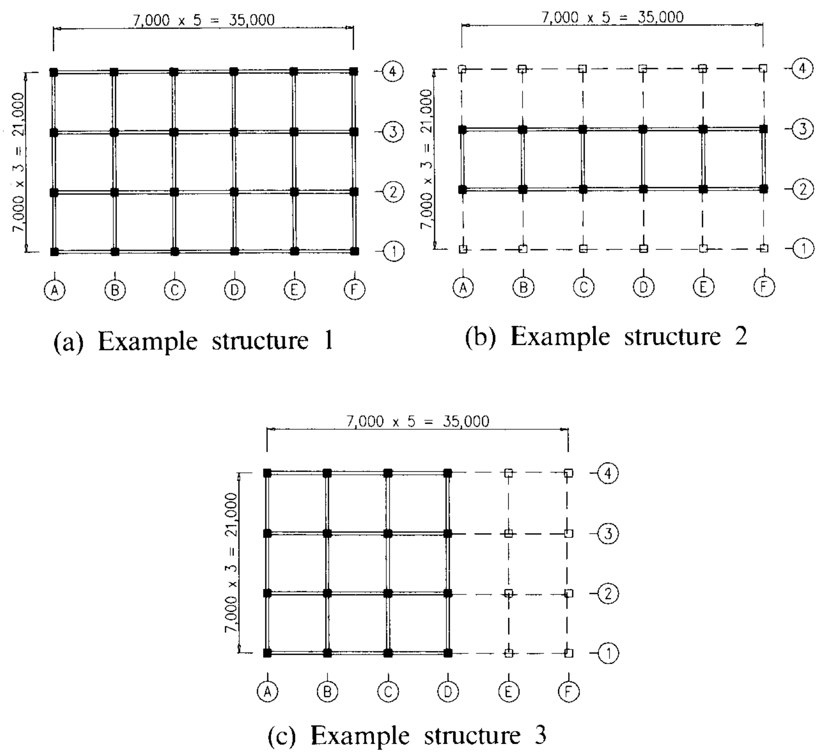


Fig. 8 Framing plan of example structures.

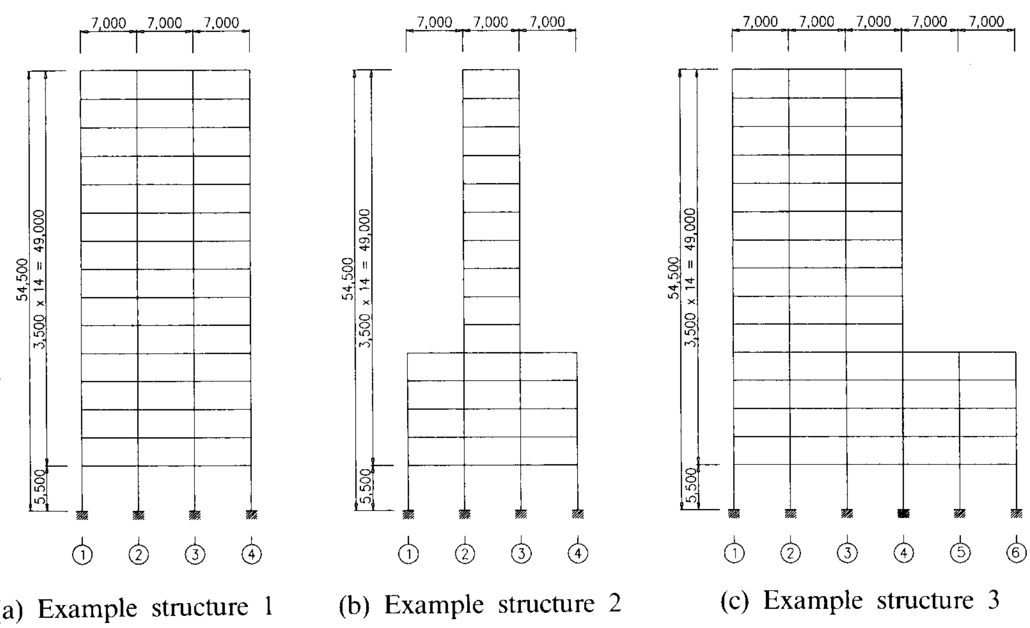


Fig. 9 Elevation of example structures.

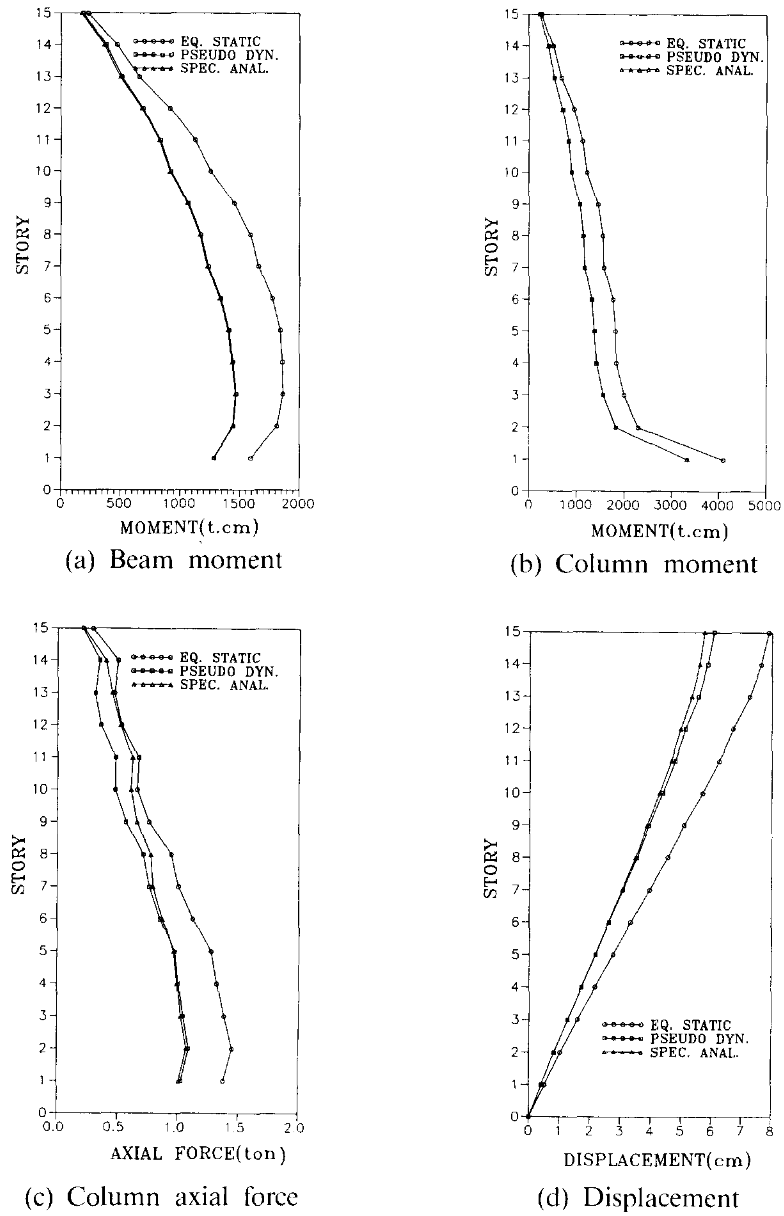
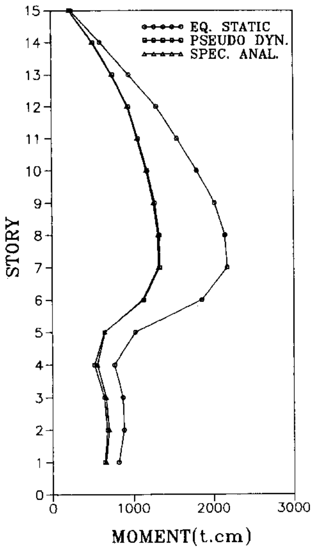


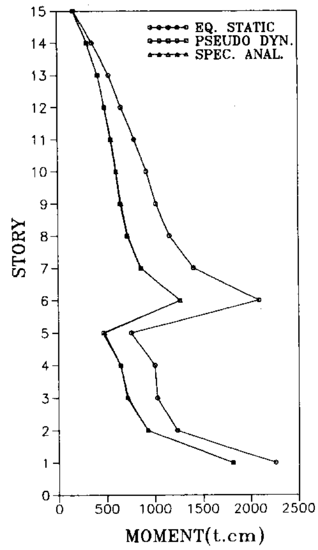
Fig. 10 Seismic responses for regular structure (Example 1).

of irregular building structures, since dynamic properties of the structure is not considered adequately. Example structure 2 is selected to demonstrate that the proposed method considers the dynamic behavior of an irregular building structure with setback in calculating seismic responses. The plan of an irregular building structure is the same as that of the regular building up to 5-th story as shown in Fig. 8(b). Section and plan above 5-th story has been modified by removing beams and columns from the regular building structure as shown in Fig. 9(b).

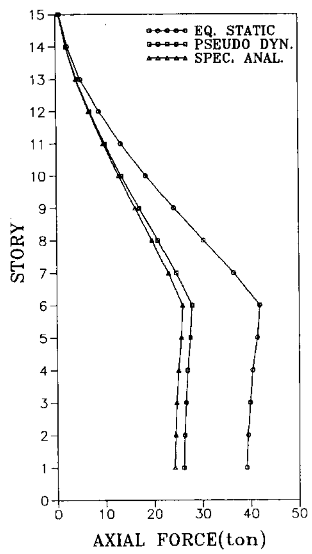
Pseudo-dynamic analysis of the irregular building structure could provide the results very close to those of the response spectrum analysis. Bending moments in beams are almost the



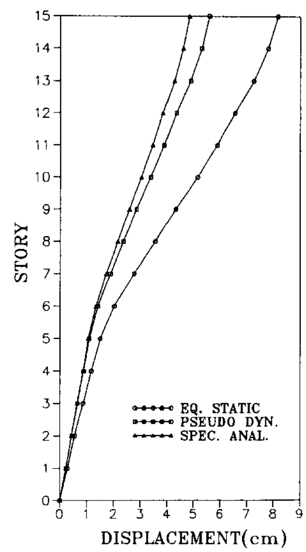
(a) Beam moment



(b) Column moment



(c) Column axial force



(d) Displacement

Fig. 11 Seismic responses for irregular structure (Example 2).

same as the results obtained from the response spectrum analysis as shown in Fig. 11(a). Bending moments in columns are very close to those obtained from the response spectrum analysis as shown in Fig. 11(b). Similar to the case of the regular framed structure, axial force in columns are slightly overestimated in lower stories of the building as compared in Fig. 11(c). The overestimation of displacements at the upper stories of the irregular building is somewhat greater than those of the regular building. However, the overestimation at the top is 15% which is much less than 70% obtained from the equivalent static force procedure as provided in Fig. 11(d).

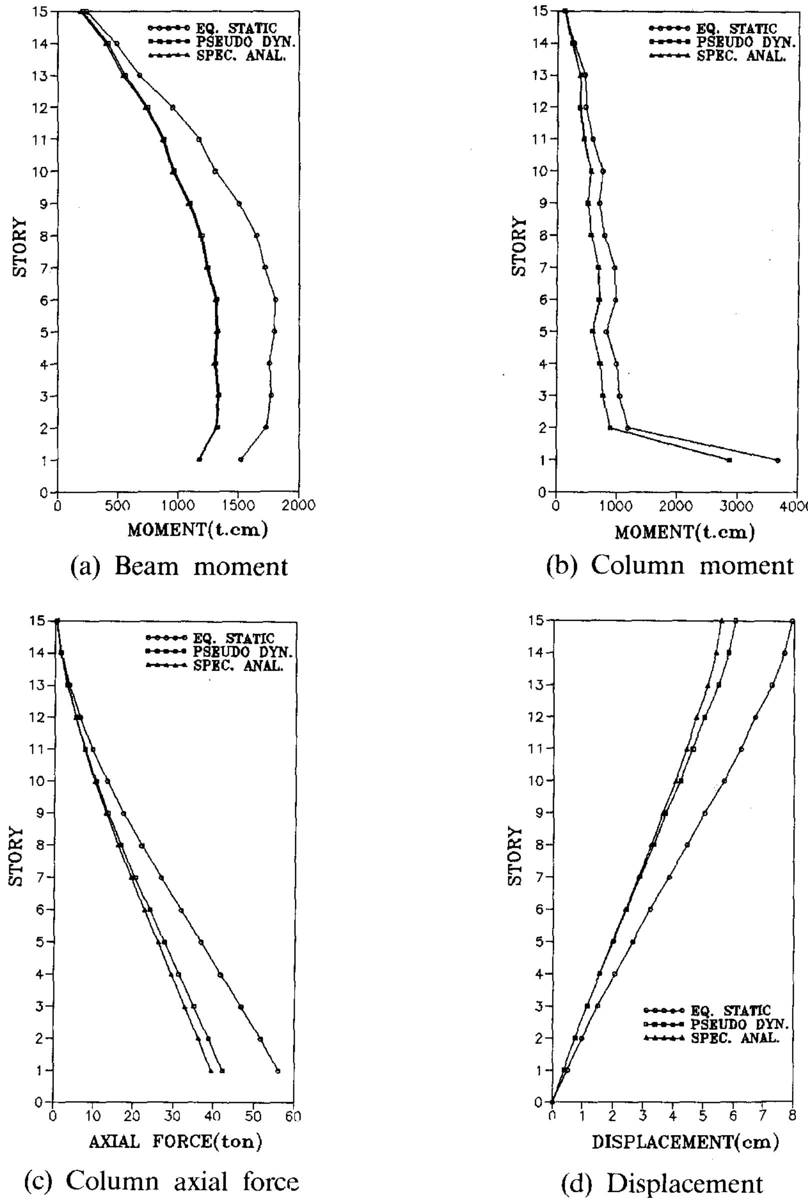


Fig. 12 Seismic responses for asymmetric structure (Example 3).

4.3. Asymmetric structure

Application of the pseudo-dynamic analysis method to an asymmetric building was verified using the example 3 structure shown in Fig. 8(c) to consider the torional effect and eccentricity of the structure. Framing plan of this example structure is the same as those of the previous examples up to 5-th story. Section and plan above 5-th story has been modified by removing all columns in lines ⓔ and ⓕ from the regular building as shown in Fig. 9(c) which is the front elevation of the structure.

The proposed analysis of the assymmetric building structure could provide the results very close to those of the response spectrum analysis. Bending moments in beams are almost the same as the results obtained from the response spectrum analysis shown in Fig. 12(a). However, the results obtained from the equivalent static force procedure overestimate more than 30% then those calculated from the response spectrum analysis. Bending moments in columns are very close to those obtained from the response spectrum analysis as shown in Fig. 12(b). Bending moments calculated from the proposed method showed about 2% underestimation at most of floors except 2 floors at the bottom which is negligible for practical design. Similar to the case of the regular framed structure, axial force in columns are slightly overestimated in lower stories of the building as compared in Fig. 12(b). The overestimation of displacements at the upper stories of the asymmetric building is slightly greater than those of the regular building. However, the overestimation at the top is about 7% which is much less than 42% obtained from the equivalent static force procedure as provided in Fig. 12(d).

4.4. Discussions on example analyses

Three types of building structures which have different dynamic characteristics were used to verify the adequacy of the proposed method. In all cases, the member forces obtained from the pseudo- dynamic analysis have been in excellent agreement with those of the response spectrum analysis. Since the story shear forces used in the proposed method are forced to be the same as those of the response spectrum analysis, corresponding member forces from two methods are supposed to be very close.

Story displacements and overturning moments obtained from the pseudo-dynamic analysis are slightly larger than those of the response spectrum analysis in some part of the structure. However, the amount of overestimation is significantly reduced by the pseudo-dynamic analysis compared to that of the equivalent static force procedure. Therefore, the proposed method is considered to provide seismic analysis results with accuracy similar to that of the response spectrum analysis.

At the same time, the results such as displacements and member forces are expressed with appropriate directions. Accordingly, automation of structural design can be accomplished easily by introducing the proposed method.

5. Conclusions and discussions

The pseudo-dynamic analysis method proposed in this study was developed to enhance the accuracy of the equivalent static force procedure to the level of the response spectrum analysis method in seismic analysis of multi-story building structures. For this purpose, part of the response spectrum analysis method was adopted for the calculation of lateral seismic forces and static analysis procedure was employed to calculate displacements and member forces. Example structures with different dynamic characteristics have been used to verify the accuracy of the proposed method and following conclusions could be drawn.

The pseudo-dynamic analysis method, developed by combining the equivalent static force procedure and the response spectrum analysis in a hybrid manner, provides accurate seismic analysis results with proper directions. Therefore, automatic design of a multi-story building structure can be performed without requiring experienced engineer's judgement.

Bending moments and shear forces in beams and columns, which are directly related to the story shear forces, can be obtained by the proposed method with the accuracy similar to that of the response spectrum analysis. Column axial forces, wall bending moments and floor displacements are slightly overestimated in part of the structures because overturning moment is overestimated by the proposed method. However, such overestimation is not deteriorating the advantages of the proposed method because it will result in minor or no effects on the design of a multistory building structure.

Extensive further study will be required to expand the application of the concept of the proposed method to structures other than multi-story buildings.

Acknowledgements

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