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A SIMPLIFIED MODEL FOR SEISMIC RESPONSE PREDICTION OF STEEL FRAME STRUCTURES

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SUMMARY

This paper proposes a simplified analysis model for seismic response prediction of steel frame structures in terms of cumulative damage parameters that account for the effects of all inelastic excursions in the seismic response. A multistory frame is reduced to an equivalent single degree of freedom system using shape vectors derived from the inelastic deflected shape due to incremental static loads and second mode shape of a structure. The plastic deformation ranges of all inelastic excursions obtained from the rain-flow cycle counting method are used to estimate the cumulative low-cycle fatigue damage. In most cases, the results obtained using the simplified model were in good agreement with those from the inelastic multistory model.

INTRODUCTION

In the seismic design of building structures, it is expected to have deformations in inelastic ranges during the occurrence of a strong earthquake. However, the expected inelastic deformations should be limited within an acceptable range in order to prevent failure due to cyclic deformations. Thus, the prediction of inelastic deformations under seismic loading conditions has become an important part in the design of structures. An assessment of the inelastic deformation demand in critical regions of a multistory structure requires a complicated analysis procedure and significant computational efforts. Therefore, it is prudent to have a simpler analysis tool in order to assess the seismic performance of a frame structure with due consideration to design alternatives and uncertainties in input ground motions.

Several studies reported in the literature have been aimed at finding simplified nonlinear models which can be used for preliminary design of a structure with the advantage of simplicity and reduced computational costs(Refs. 1,2). But most of their simple analytical models had little interest in the interstory drifts and inelastic deformations of components which lead to the cumulative fatigue damage to a structure.

This paper introduces an equivalent single degree of freedom (ESDOF) model for seismic response prediction of multistory steel frames. Story displacements and interstory drifts are calculated from the inelastic dynamic response of ESDOF system using shape vectors which can account for the effects of first and second modes. The plastic deformation ranges of all inelastic excursions obtained using the rain-flow cycle counting methods are utilized to estimate the cumulative low-cycle fatigue damage.

EQUIVALENT SINGLE DEGREE OF FREEDOM MODEL

An equivalent single degree of freedom system for a multistory frame can be obtained by deriving a single degree of freedom equation from the equations of dynamic equilibrium for a multistory frame which is in the following form;

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = -[M]\{1\}\ddot{x}_g \tag{1}$$

where {X} is the relative story displacement vector and damping and stiffness matrices [C] and [K] are condensed matrices obtained by eliminating the degrees of freedom assigned to rotations and vertical displacements. The mass matrix [M] is a diagonal matrix for the lumped story mass at each floor level. In the development of the ESDOF model, it is assumed that the deflected shape of a N-story frame can be represented by a single shape vector. Thus, the relative story displacements of a multistory frame {X} can be approximately related to the displacement of a corresponding ESDOF system x by a shape vector $\{D_x\}$ as follows;

$$\{X\} \approx \{D_x\}x \tag{2}$$

where $\{D_x\}$ is a vector that describes the deflected shape of the multistory frame. Velocity and acceleration of the multistory frame can be related to those of a corresponding ESDOF model in the same manner. The shape vector $\{D_x\}$ obtained from the deflected shape of a multistory frame can be normalized to a unique shape vector {D} which is independent of the amplitude of deflection by using $\{D_x\}$ in lieu of {X} in Eq. 1. Using the normalized shape vector {D}, the dynamic equilibrium equation of a multistory frame can be approximately reduced to the dynamic equilibrium equation of an ESDOF system as follows;

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g \tag{3}$$

where the ESDOF system properties m, c, and k are

$$m = \sum_{i=1}^{N} M_i D_i^2 \qquad c = \sum_{i=1}^{N}\sum_{j=1}^{N} C_{ij} D_i D_j \qquad k = \sum_{i=1}^{N}\sum_{j=1}^{N} K_{ij} D_i D_j \tag{4}$$

The mass and damping of the ESDOF system is assumed to remain constant both in elastic and inelastic ranges. For all cases the damping ratio of the ESDOF system was found to be almost the same as the first mode damping ratio of a multistory frame. The stiffness of the ESDOF system in the elastic range can be obtained from the stiffness matrix [K] and the shape vector {D} using Eq. 4. However, in the inelastic range, the matrix [K] is frequently changed and it is impractical to determine the stiffness of the ESDOF model for every inelastic excursions. An alternative method is employed to find the stiffness of the ESDOF system in the inelastic range. Assuming that the deflected shape of a multistory frame can be represented by a single shape vector even in the inelastic range, the shape vector {D} is obtained from a deflected shape {X} using Eq. 3.

$$\{D\} = \frac{\sum_{i=1}^{N} M_i X_i}{\sum_{i=1}^{N} M_i X_i^2}\{X\} \tag{5}$$

Substituting Eq. 5 into Eq. 2 we obtain the corresponding displacement of the ESDOF system from the deflected shape {X} as follows;

$$x \approx \frac{\sum_{i=1}^{N} M_i X_i^2}{\sum_{i=1}^{N} M_i X_i} \tag{6}$$

In order to obtain representative values for {X}, it was decided to subject the frame to a series of incremental static loads. For every inelastic load step, the deflected shape likely will change because of the redistribution of bending moments. But for regular frames the value of x, as obtained from Eq. 6, appears to be an acceptable representation of the inelastic displacement of the ESDOF systems. Since the restoring force f of the ESDOF system at the displacement x is considered to be equivalent to the base shear V of the multistory frame at the displacement {X}, the V-x relationship obtained from incremental static analysis of a multistory model represents the f-x relationship of the ESDOF system. The force-displacement relationships of the ESDOF systems for regular multistory frames turned out to be close to bilinear. Therefore, a bilinear hysteresis relationship is used to represent the force-displacement relationship of the ESDOF system. The strain hardening ratio p and the yield force f_y for the ESDOF model are determined to fit the force-displacement relationship shown in Fig.1.

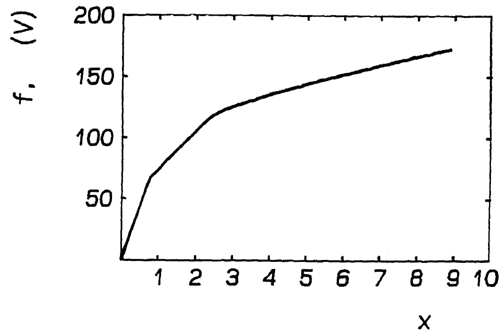

Fig. 1 Relationship Between Equivalent Displacement and Base Shear

Table 1. Characteristic of ESDOF System

	10 Story	20 Story
Period	1.0	2.0
Weight(kips)	812.	1529.
Yield Force	113.	115.
Stiffness Hardening Ratio	0.093	0.060

ESTIMATION OF THE INELASTIC RESPONSE OF MULTISTORY FRAMES

Story Displacement and Story Deformation The time history of story displacements of a multistory frame {X(t)} can be estimated from the displacement time history x(t) of the ESDOF system using the shape vector {D} as follows;

$$\{X(t)\} = \{D\}x(t) \tag{7}$$

Story deformation at a floor level is defined as the average of interstory drift angles in adjacent stories. Using the shape vector {D}, the story deformation time history at the i-th level is given as

$$\delta_i(t) = \frac{1}{2}\left(\frac{D_{i+1}-D_i}{H_i} + \frac{D_i-D_{i-1}}{H_{i-1}}\right) \tag{8}$$

Shape Vectors Since damage parameters are related mainly to larger inelastic deformations, the shape vector needs to have properties that permit an adequate prediction of large inelastic deformations. For this purpose a series of deflected shapes are obtained from incremental static analysis of the multistory frame. Then the one which corresponds to the maximum displacement of the ESDOF system is selected and normalized to find the shape vector $\{D_1\}$ to account for the contribution of the first mode vibration with large inelastic deformations using Eq. 5.

$$\{D_1\} = \frac{\sum_{i=1}^{N} M_i X_i}{\sum_{i=1}^{N} M_i X_i^2}\{X\} \tag{9}$$

The second shape vector $\{D_2\}$ is used to supplement the effect of the second or higher modes other than the first one. The second vector is obtained by normalizing the second mode shape of a multistory by substituting $\{\phi_2\}$ in lieu of $\{X\}$ in Eq. 9.

$$\{D_2\} = \frac{\sum_{i=1}^{N} M_i\phi_{2i}}{\sum_{i=1}^{N} M_i\phi_{2i}^2}\{\phi_2\} \tag{10}$$

Since the third or higher modes will not contribute major effect on the response of a multistory frame, only two shape vectors are used for the simplicity in the estimation of the seismic response of a multistory frame.

Combination of Response Two mass participation factors are obtained using the first and second shape vectors to determine the ratio of contribution of each mode as follows;

$$\alpha_1 = \frac{(\sum_{i=1}^{N} M_i D_{1i})^2}{\sum_{i=1}^{N} M_i\ D_{1i}^2} \qquad \alpha_2 = \frac{(\sum_{i=1}^{N} M_i D_{2i})^2}{\sum_{i=1}^{N} M_i\ D_{2i}^2} \tag{11}$$

where M_i is the mass of i^{th} story. The story displacement component $\{X_1\}$ and $\{X_2\}$ of a multistory frame are obtained by incorporating the displacement of the ESDOF model and two shape vectors in the following manner;

$$\{X_1\} = \{D_1\}x \qquad \{X_2\} = \{D_2\}x \tag{12}$$

Then story displacement vector is obtained by the square root of the sum of squares(SRSS) of each story displacement components, X_{1i} and X_{2i}. Story deformation components, δ_{1i} and δ_{2i}, are obtained by substituting the story displacement component into Eq. 12. The story deformation of each story is obtained as the SRSS of story deformation component δ_{1i} and δ_{2i}.

DAMAGE ESTIMATION FOR FRAME STRUCTURES

Story Deformation Ranges The story deformation time history is converted into story deformation ranges, using the rain flow cycle counting method. The yield level of story deformations are needed to separate inelastic deformation ranges from total story deformation ranges. By an approximate method, the yield level of story deformations for regular frames can be obtained from the story free-body as follows;

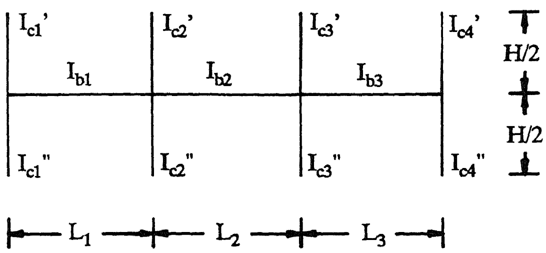

Fig. 2 Story Free-Body for Estimation of Yield Story Deformation

$$\delta_y = \frac{1}{n}\frac{1}{6E}\sum\frac{(M_{ph})_i L_i}{I_{bi}} + \frac{1}{n+1}\frac{1}{12E}\sum (M_{ph})_i\left[\frac{1}{I_{ci}'} + \frac{1}{I_{ci}''}\right] \tag{13}$$

Plastic story deformation ranges are obtained by subtracting twice the elastic deformations from story deformation ranges.

Damage Model The conventional procedure for assessing the seismic performance of structures is to evaluate the maximum deformation demand for the complete structure or for individual critical components. Because of the cyclic nature of seismic response, it is more appropriate to consider the cumulative effect of all inelastic excursions rather than the maximum excursion alone. For steel frame structures , simple cumulative damage models can be used. These models which are only approximate, utilize the Coffin-Manson relationship(Refs 3,4) and Miner's rule(Ref. 5) of linear damage accumulation to assess component performance. Using these two relationships and taking the story deformation for the selected deformation quantity, the accumulated damage after N cycles of different plastic deformation ranges is given as

$$D = \sum_{i=1}^{N} \left(\frac{\Delta\delta_{pi}}{\delta_y}\right)^{1.5} \tag{14}$$

where D is a cumulative damage parameter, N is number of plastic deformation ranges, δ_p is plastic deformation ranges and δ_y is yield story deformation. As an additional damage parameter, the normalized maximum plastic deformation range $(\Delta\delta_p/\delta_y)_{max}$ is evaluated in this study. In concept this parameter is similar to the maximum ductility ratio, but it identifies the maximum deformation range rather than the maximum deformation amplitude. For this cumulative damage model, the rain flow cycle counting method is used in order to convert the irregular time history of story deformation into a many closed cycles as possible(Ref. 6).

PREDICTION OF SEISMIC RESPONSE OF MULTISTORY FRAMES

Damage parameters are predicted for a series of generic frames with various design parameters such as geometry of the structure, fundamental period, design base shear for using the proposed ESDOF model and the results are compared to those obtained using multistory frame models. Nonlinear dynamic analysis of ESDOF models and multistory models are performed using the computer codes NONSPEC (Ref. 7) and STANON (Ref. 8). All frames are assumed to be single bay frames with all stories being of equal height. The same mass and gravity load moments are assigned to each story. Inelastic deformations are limited to plastic hinge. The damping ratio for all modes is assumed to be 5 percent. Each frame is designed for gravity loads and seismic loads using the ATC-3 ground spectra for highly seismic regions (Aa=Av=0.4). The input ground motions are the S90E component of the 1940 El Centro earthquake and the N21E component of the 1952 Taft earthquake, which are scaled to a common peak ground acceleration of 0.4g in order to have acceleration spectra which match satisfactorily with the ATC-3 ground motion spectra in the period range of interest. Presented in this paper are the results for two example structures with 10 and 20 stories designed for ATC R factor equal to 8 and subjected to the EL Centro earthquake. Maximum story deformations $\{\delta_i\}_{max}$ normalized maximum plastic deformation ranges $(\Delta\delta_p/\delta_y)_{max}$, and cumulative damage parameters D for example structures are shown in Fig 3,4.

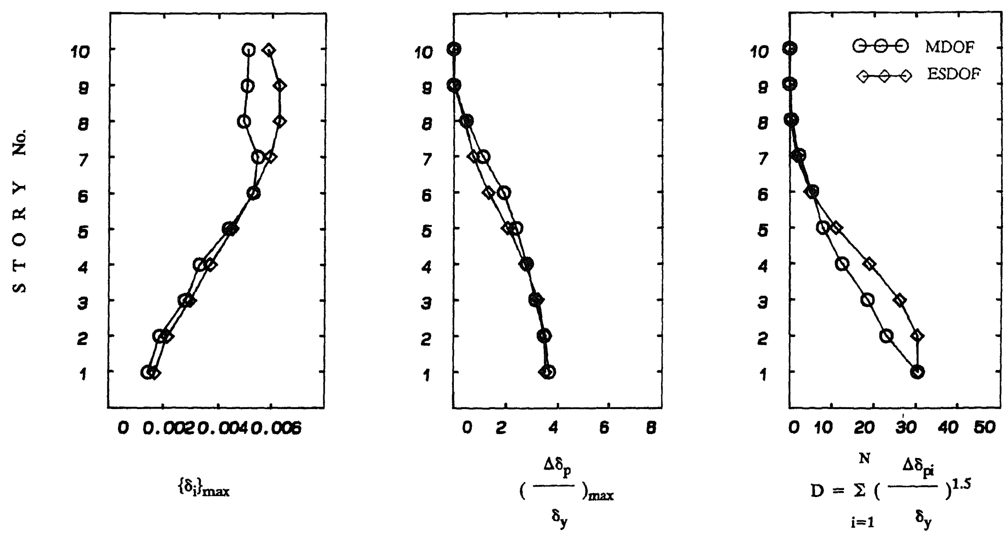

Fig. 3 Damage Response of 10 Story Frame

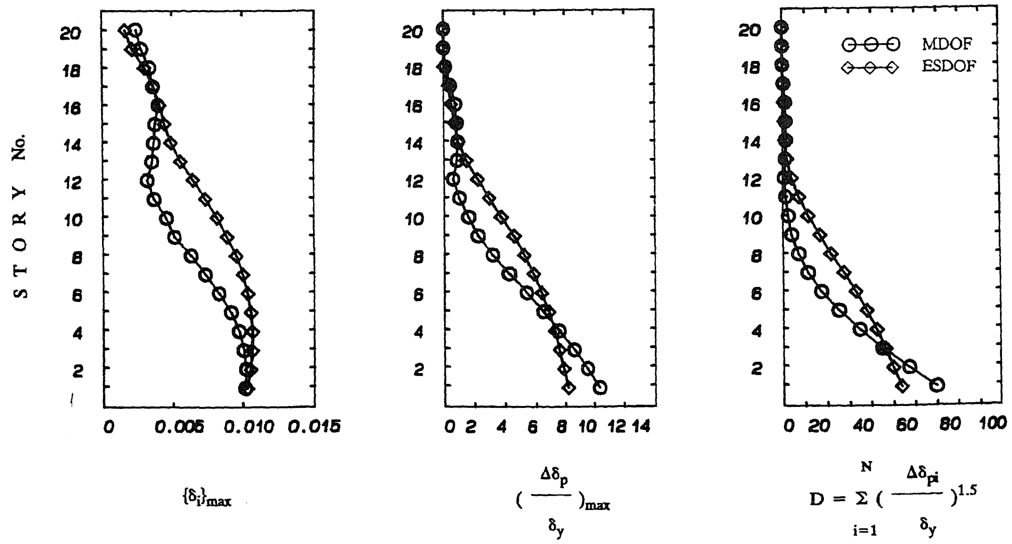

Fig. 4 Damage Response of 20 Story Frame

Damage parameters predicted for most of generic frames studied as well as these example structures using the ESDOF model are considered to be acceptable for the purpose of preliminary design of structures. However, damage prediction for structures with more than 15 stories and designed for ATC R factor equal to 4 was less accurate than those for example structures.

CONCLUSIONS

Proposed ESDOF model results in an adequate seismic response prediction for a multistory frame when the structure is regular and larger plastic deformations are expected. The accuracy of damage parameters prediction using the ESDOF model is deteriorated when multistory building has significant irregularities, increased number of stories or smaller plastic deformations. Therefore the use of the ESDOF model is not recommended for very tall building structures or irregular structures. However the ESDOF model is considered to provide better prediction of damage parameters than linear multistory models which can not account for the nonlinear characteristics of structures.

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