DESIGN OF THREE DIMENSIONAL FRAMES USING INTERACTIVE GRAPHICS

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SUMMARY

This paper describes some of the analysis and design tools that have been developed in a new interactive graphics computer aided earthquake design system. The analytical tools range from simple elastic to sophisticated nonlinear methods. The paper focuses on the methods that employ linear elastic dynamic analysis in conjunction with approximate procedures for accounting for nonlinearity and, in particular, on a response spectrum design method. Use of the method is illustrated through application to the design of a simple frame.

INTRODUCTION

The authors and associates at Cornell have been conducting research aimed at the advancement of practical, economical methods for the nonlinear analysis and design of three dimensional steel framed structures. As part of this research, an advanced system for interactive design of statically loaded systems has been developed (Ref. 1 and Ref. 2). Comparable capability for earthquake design is under development. Analysis and design at several levels will be possible: from code related equivalent static load procedures, through approximate linear and nonlinear dynamic methods, to advance nonlinear analysis. One of the intermediate level methods - an interactive response spectrum technique - is the subject of this paper.

Of the dynamic analysis methods the response spectrum analysis method is often favored because it is less expensive than more accurate nonlinear time-history analysis. In assessing resistance to strong earthquakes, it is necessary to account in some way for the inelastic deformation characteristics of the structure. Since conventional response spectrum analyses are only valid so long as the structure remains elastic, inelastic response spectrum methods have been used to model the structure well past yield. These inelastic spectra have been derived either by considering the response of a nonlinear single degree of freedom system or by scaling elastic spectra for specific ductility and damping (Ref. 3). Although the approximations and shortcomings of these methods are well known, they are at present useful techniques for seismic design where a nonlinear time-history analysis is not feasible or when it would, in itself, be of doubtful accuracy. The methods to be described here are promising nonlinear response spectrum techniques and, further, their use is greatly facilitated by incorporation in an advanced interactive graphics system.

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GENERAL DESCRIPTION

The research is conducted in an advanced technology, interactive computer graphics environment that includes vector refresh graphic displays, color raster graphics, and a 32 bit virtual memory VAX 11-780 minicomputer. The system contains a problem definition module - the "preprocessor" - in which the structure geometry, boundary conditions, and member properties are specified (Ref. 4) and an analysis and design module which has three main sections: 1) Input, 2) Analysis, and 3) Design. Figure 1 shows the components of the program which are interactively accessed during a design.

The input section allows the definition of different types of seismic loads. The user may interactively generate and distribute a UBC or ATC lateral equivalent static seismic load along a column line of a frame. In a three dimensional frame the eccentricity of the center of rigidity fromthe center of mass at each level is evaluated to generate the torque which is then distributed as shear forces to the columns at that level. For dynamic analysis ground motions may be defined by an earthquake record or a response spectrum. Either form may be specified in any of the three global directions. To assist the user, a library of earthquake records has been developed. The records may be displayed in sequence. Selection of the desired earthquake is made from the display (Fig. 2. In this and some of the other figures small lettering contains no pertinent information and is only included to illustrate the nature of the computer graphics displays). An algorithm has also been implemented to generate response spectra from an accelogram. It uses the Newmark linear acceleration method. To generate inelastic response spectra one has a choice of elastic-strain hardening or Ramberg-Osgood nonlinear models. The inelastic spectra are generated for a specified ductility. An interpolation procedure is involved since the response of systems with arbitarily selected yield levels will seldom correspond to the desired ductility values. In addition, code type Newmark-Blume-Kapur spectra may be generated for a specified maximum ground acceleration, damping, and ductility.

The analysis program used in the present study program consists of a set of modules developed for linear dynamic analysis of three dimensional frames (Ref. 5). The building model ensures full displacement compatibility. The program also has an option in which any floor may be assumed to be infinitely rigid in its own plane, and infinitely flexible out of its plane. Use of this option significantly reduces the number of degrees of freedom in the idealization. The analysis procedures utilize a lumped mass idealization, resulting in a diagonal mass matrix. Those degrees of freedom having no associated mass are condensed out by static condensation. The program has at present three main options for analysis 1) static, 2) modal, and 3) direct integration (Fig. 1). The static analysis uses the equivalent static lateral forces combined with other different load types such as dead, live, etc. In the modal analysis section elastic eigenvalues and eigenvectors are generated before proceeding to perform either a modal time-history or a response spectrum analysis. Figure 3 shows the eigen analysis page where the periods and mode shapes may be observed. Integration for the modal analysis is carried out over the uncoupled modal co-ordinates by evaluating the analytic response to a linearized forcing function. The response spectrum analysis (described below) uses elastic or inelastic spectra and an approximate method to take account of nonlinearity. Direct time integration is performed either by an explicit central difference method or by the Newmark method of implicit integration. Figure 4 shows a time history page with the structure displaced shape, modal displacement history, and analysis information being monitored during analysis. Algorithms developed for full material and geometric nonlinear dynamic analysis of three dimensional frames are presently being incorporated in the system described here.

The redesign section uses the design procedure implemented in the static design system mentioned above (Ref. 1 and Ref. 2). Essentially it uses an analysis/design/re-analysis approach which employs the results of the previous analysis to generate a new design by evaluating the response of individual members and re-proportioning members that are either under- or overdesigned so that they satisfy their design criteria. These criteria are from an applicable specification and are defined in the form of design equations. Figure 5 shows the page for interactively specifying design equations. The re-design is performed either by having the program choose a new set of sections that satisfy the specified design equations or by interactively replacing the current sections of a particular group by those of the user's own choice.

RESPONSE SPECTRUM METHOD

The principal advantages of the modal response spectrum method are that a step by step time-history analysis is not needed and the number of modes to be consider can be limited. Often only the first few modes of vibration significantly affect the structural response. The number of modes to be combined and the corresponding modal damping ratios to be used in the analysis may be specified interactively by the user. The modal displacement maxima generated from the response spectrum analysis may be combined by any one of the following rules: 1) SRSS - the square root of the sum of the squares of the maximum response, 2) ABS - sum of absolute values of the same quantities, and 3) Combined SRSS and ABS - the responses of the modes that are closely coupled (with frequencies within 10% of the smallest in a group of frequencies) combined by ABS with the results of this computation combined with the other modes in an SRSS fashion. Although inelastic response spectra may be used to account for nonlinearity, a simple iterative algorithm using an equivalent linearization criterion has been implemented to take account of the period shift due to inelasticity. One of many studies on equivalent linearization for multidegree of freedom systems was performed by Guerra and Esteva (Ref. 7). The method developed here follows this work closely, and is based on deriving equivalent stiffness components which are obtained as averages of their corresponding values when the component displacement is made to vary from zero to maximum. Thus:

$$k'_i = \frac{1}{D_i} \int_0^{D_i} k_i(x)\, dx$$

k' - modified stiffness

k(x) - secant stiffness of the force displacement relation
i - index that identifies the component
D - maximum displacement

The assumptions used are:

1) The masses of the equivalent system are equal to those of the original system.

2) Only flexural member stiffness is considered. Axial, shear, and torsion effects and their interaction with flexture are neglected.

3) For a lateral seismic load the frame may be assumed to have flex points at mid-span of beams and mid-height of columns. Thus for an elastic-plastic force deformation behaviour we have a system as shown in Figure 6.

The resulting equivalent flexural stiffness is

$$k_i' = \frac{k_i}{\mu}\left[1 + \ln \mu\right]$$

μ - rotational ductility (see Fig. 6)

Computation of the response proceeds iteratively. The new estimates of equivalent stiffness are obtained using the maximum displacments from the initial analysis and the cycle is repeated until the period shift in two consecutive cycles is nearly equal. The analysis results include member forces, ductility, and story drift for the approximate nonlinear configuration. The equivalent linearization feature may be used with either an elastic or inelastic response spectrum.

DESIGN EXAMPLE

As a simple illustration of some of the capabilities and options of the system, the results of a study of a 10 story plane frame are presented. The frame was first designed using an inelastic response spectrum, elastic eigen analysis and no equivalent linearization. This frame was then re-analyzed using an elastic response spectrum and equivalent linearization. The SRSS rule was used to combine the modal maxima in both cases. The ductility demands associated with the two methods is compared. The seismic load used as a basis for both analysis was the N-S component of the 1940 El Centro earthquake, scaled to a peak acceleration of 0.5g. This accelogram was used to generate the two spectra. One was an elastic spectrum for 5% damping. The other was an inelastic spectrum using the elastic-strain hardening response model for ductility of 4 and 5% damping (Fig. 7).

For the inelastic response spectrum design the final sections derived are shown on Figure 8(a). The first two periods of the designed frame were $T_1 = 2.341$s and $T_2 = 0.895$s.

The same frame was analysed by the equivalent linearization method using the elastic spectrum to study the drift and the ductility demand. Figure 8(b) shows the results in the form of the rotation ductility and the drift (the relative displacement between two levels divided by the story height) at each story. The periods at the end of the linearization iterations shifted to $T_1 = 2.446$s and $T_2 = 0.924$s. The maximum drift was 0.024

(at story 4), and the maximum rotation ductility was 3.05 (at level 6). Hence the linearization approximation predicts a lower ductility demand than the design target of 4.

CONCLUSION

The interactive computer graphics analysis and design system described here can greatly facilitate computer aided earthquake design of three dimensional steel frames. A promising response spectrum method with an equivalent linearization technique is presented and studies to compare the results from this method with those obtained by more exact nonlinear methods is underway. One objective of this research is to evaluate the capability of this linearization method for taking into account nonuniform yielding in structures. Research with emphasis on nonlinear, three-dimensional dynamic analysis and on the practical use of advanced methods of analyses in design is also continuing.

ACKNOWLEDGEMENTS

This research was supported by Grant No. CEE-8117028 from the U.S. National Science Foundation. Many of the original computer graphics and analysis modules used were developed by Dr. C. I. Pesquera and Dr. M. Gattass. Their contributions are gratefully acknowledged. The authors also gratefully acknowledge the contributions of Professor J. F. Abel as Co-Principal-Investigator and Professor D. P. Greenberg, as Director of the Computer Graphics Laboratory.

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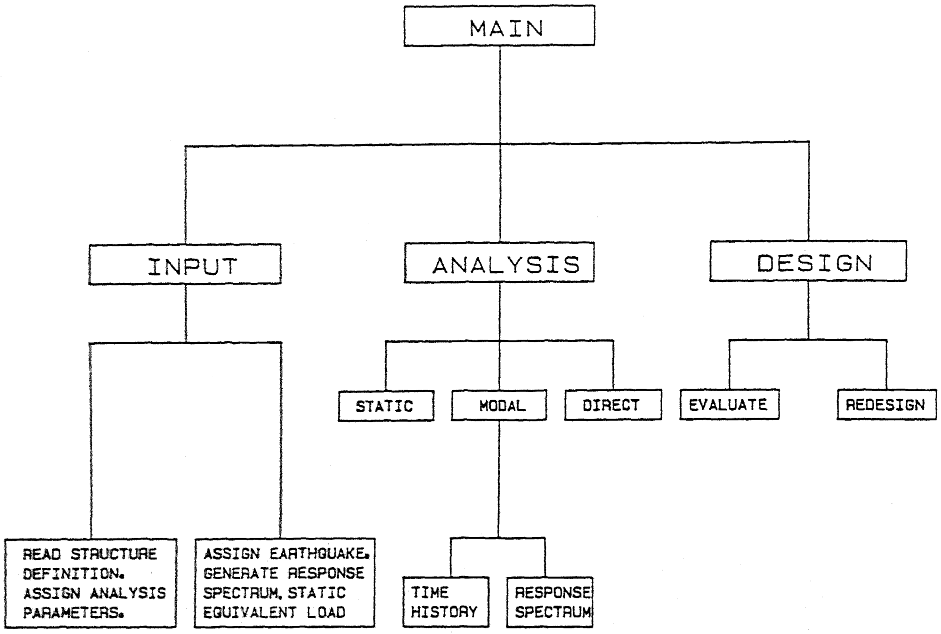


Fig. 1 Components of the Program.

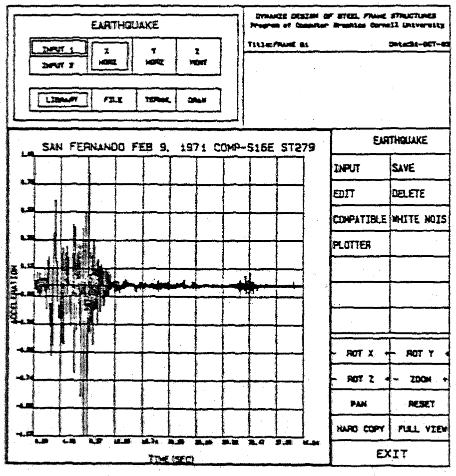


Fig. 2 Earthquake Assignment.

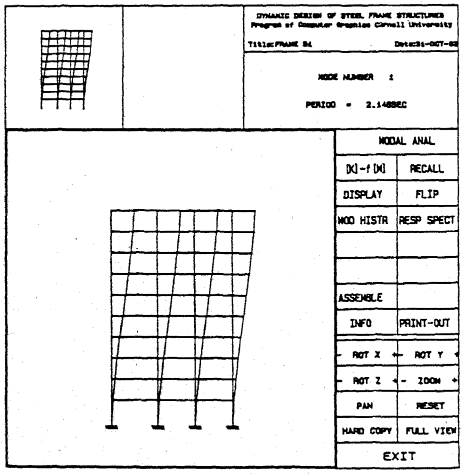
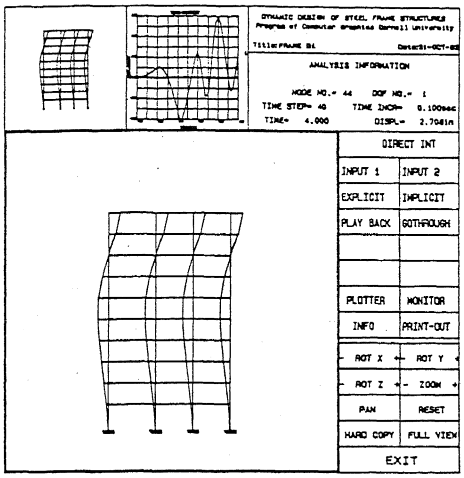


Fig. 3 Analysis and Display of Periods and Mode Shapes.



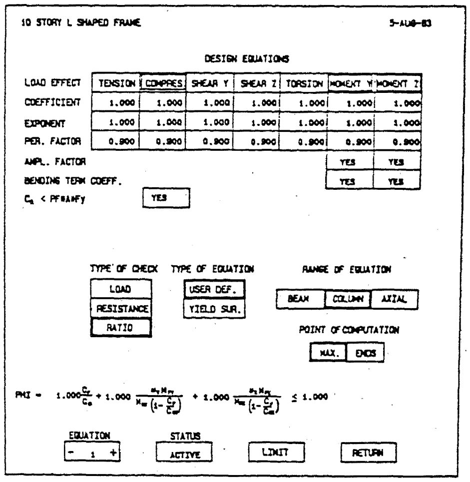
DYNAMIC DESIGN OF STEEL FRAME STRUCTURES
Program of Computer Graphics Cornell University

Title: FRAME 81 Date: 21-OCT-8

ANALYSIS INFORMATION

NODE NO.= 44 DOF NO.= 1
TIME STEP= 40 TIME INCR= 0.100sec
TIME= 4.000 DISPL= 2.7061in

Fig. 4 Time History Analysis and Display.



10 STORY L SHAPED FRAME 5-AUG-83

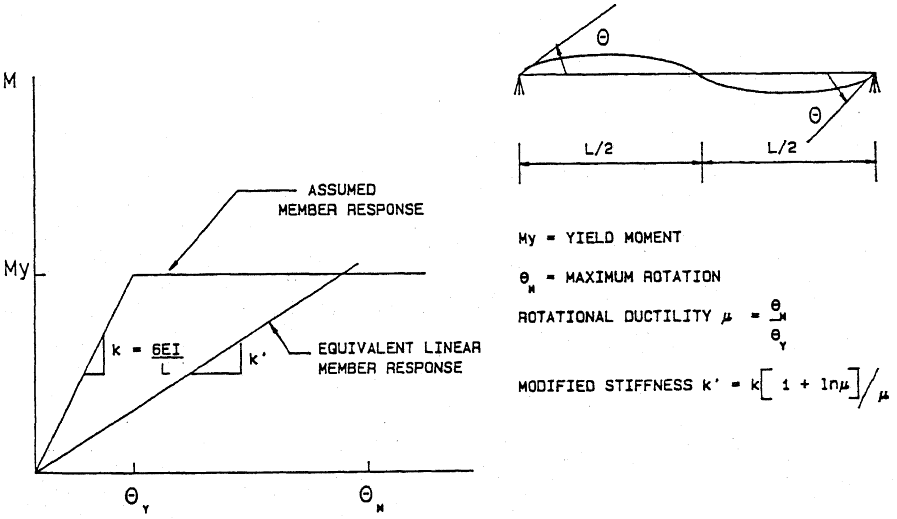
DESIGN EQUATIONS

LOAD EFFECT	TENSION	COMPRES	SHEAR Y	SHEAR Z	TORSION	MOMENT Y	MOMENT Z
COEFFICIENT	1.000	1.000	1.000	1.000	1.000	1.000	1.000
EXPONENT	1.000	1.000	1.000	1.000	1.000	1.000	1.000
PER. FACTOR	0.900	0.900	0.900	0.900	0.900	0.900	0.900
AMPL. FACTOR						YES	YES
BENDING TERM COEFF.						YES	YES

C_f < PF*A*Fy YES

$$PHI = 1.000\frac{C_f}{C_r} + 1.000\frac{\omega_y M_{fy}}{M_{ry}\left(1-\frac{C_f}{C_{ey}}\right)} + 1.000\frac{\omega_z M_{fz}}{M_{rz}\left(1-\frac{C_f}{C_{ez}}\right)} \leq 1.000$$

Fig. 5 Design Equation Definition.



My = YIELD MOMENT

Θ_M = MAXIMUM ROTATION

ROTATIONAL DUCTILITY $\mu = \frac{\Theta_M}{\Theta_Y}$

MODIFIED STIFFNESS $k' = k\left[1 + \ln\mu\right]/\mu$

Fig. 6 Equivalent Linearization

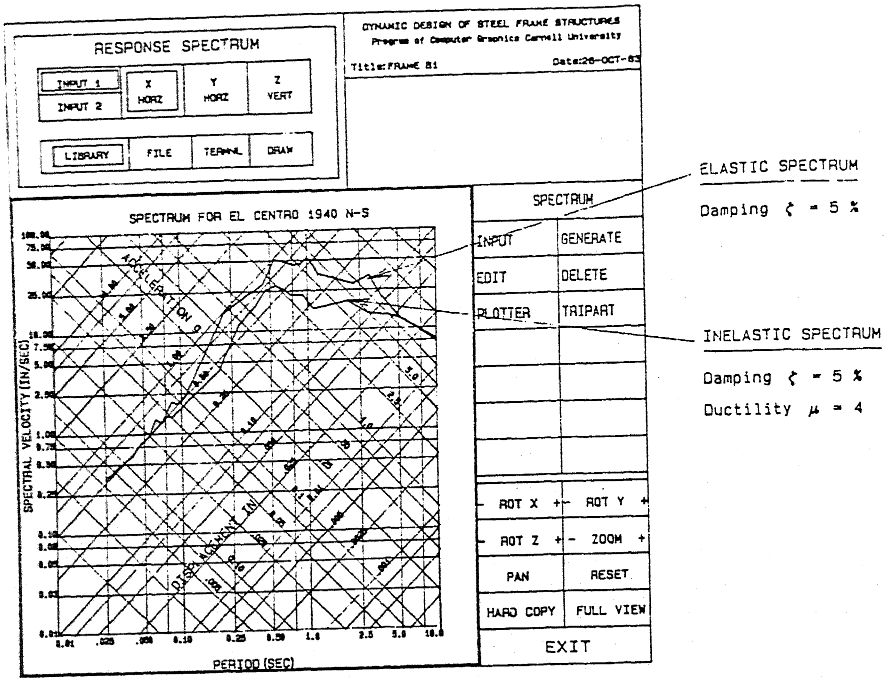
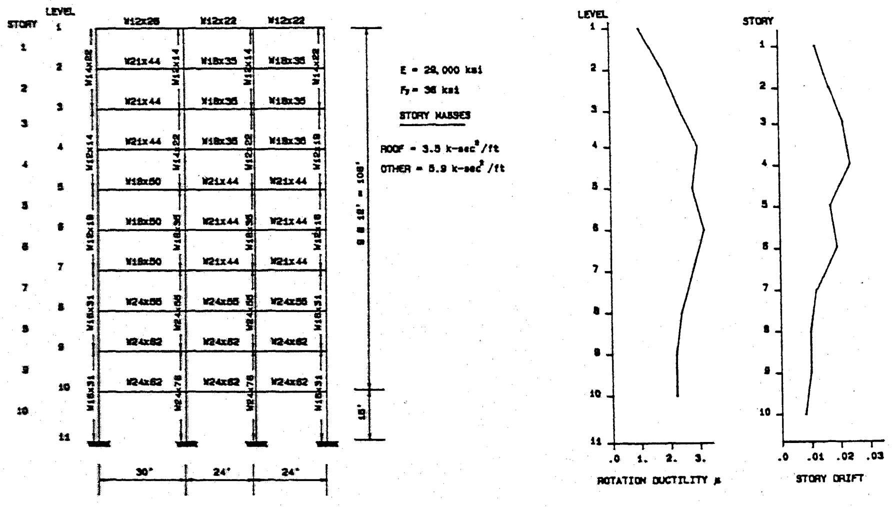


Fig. 7 Response Spectra Used for the Design Example.



(a)

(b)

Fig. 8 Results of the Design Example.