Interactive Computer Graphics in Steel Analysis/Design— a Progress Report

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This is a progress report of research on the development of a system of computer-aided design. It will provide for the description of a two- or three-dimensional steel frame to the computer, preliminary and final analysis of the frame, and review of its adequacy under both service and ultimate loads. Included are provisions for conducting interactively the normal iterative procedures for refining a trial design to its final state. Several levels of analysis are available, from conventional linear elastic analysis, to full geometric and material nonlinear analysis. Design equations are incorporated for use in checking compliance with common standards such as the Specification of the American Institute of Steel Construction[1] and the *Limit States Specification* of the Canadian Standards Association.[2] The system is flexible; the user does not have to follow a rigid, prescribed routine.

It is a progress report in several respects. Some basic provisions, such as procedures for handling local and lateral buckling, need refinement. Also, of course, a computer-aided design system can never be truly complete. There will always be need to incorporate advances in analysis and in the understanding of structures. Further, the system to be described is not a commercial software package. It is the product of continuing research in structural engineering and the ways in which advanced technology can enhance the analysis and proportioning of civil engineering structures. Nevertheless, although the work continues, it has reached the stage where the procedures described are believed to be of practical utility and suited to the needs of many structural design organizations.

Reactions to computer-aided design tend to be emotional. The situation is not helped by catchlines such as the title of a recent article in an engineering publication, "Computer-Aided Everything." Hyperbole of this sort causes the gullible to anticipate a marvelous new world, and the wary to fear an uncontrollable technology. Neither extreme is justified. It is hoped the work described here demonstrates the potential for application of interactive computer graphics to engineering of steel structures, but at the same time makes it clear that computer-aided design can—and should—accommodate the essentials of good engineering: theory, experiment, experience and common sense.

BACKGROUND

A basic aim of the research is to address a chronic problem in structural engineering: how to incorporate the ever increasing knowledge of structural response and behavior in the place where it should be used—the design process—in ways that are clear to the practitioner. Interactive computer graphics is a medium that can be invaluable in support of two related endeavors of this sort. First, in valid academic research in problems of nonlinear behavior and analysis; and, second, in the application of rigorous nonlinear analytical methods to design in ways that do not require abandonment of the traditional safeguards essential to the assurance of a sound structure.[3]

Nonlinearity—It is generally understood there is no such thing as a truly linear structure or structural component. Departures from linearity range from the insignificant to those that make predictions of behavior based on linear elastic theory completely unrealistic. Some have always been recognized in design. For example, from early days the fact that statically loaded bolted and welded joints behave nonlinearly prior to failure has been accounted for implicitly in the establishment of design stresses. Also, after a stage of essentially linear response, a steel member or frame behaves nonlinearly as a result of yielding, large elastic displacements, or a combination of the two. The consequences of these nonlinearities have been accounted for more or less indirectly in practice through a number of devices: empirical equations or modifying coefficients, adjustment of allowable stress in recognition of post yielding

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resistance, amplification factors that allow for some second order effects, approximate second order methods of analysis, plastic analysis and design and so on.

These devices have played essential roles in design and will continue to do so. But many are very approximate in nature or limited in scope. There is increasing recognition of the desirability of treating nonlinearity explicitly where it is important and where practical methods with good theoretical and experimental support are available. Evidence of this is in the general statement on stability in the present AISC Specification, "Design consideration should be given to significant load effects resulting from the deflected shape of the structure."[1]

In Technical Memorandum No. 5 of the Steel Structures Research Council it is noted, "In addition to the material nonlinearities, geometric imperfections, loading history, large deflections, post-buckling strength and behavior and connection response may affect significantly the limit of structural usefulness." In consequence, the Memorandum recommends, "Maximum strength, determined by evaluation of those effects that influence significantly the maximum load-resisting capacity of a frame, member or element, is the proper basis for the establishment of strength criteria."[4] Both the AISC and SSRC statements are those of principle that require explicit consideration of nonlinearity. In many cases, this can be accomplished adequately through application of some of the devices mentioned above. But to follow these precepts conscientiously, more fundamental methods are required.

Reasonably rigorous methods of nonlinear analysis that account for both geometric and material nonlinearity have been available for a number of years. Prior to the advent of the computer, however, their use in civil engineering structures was rare and generally limited to consideration of geometric nonlinearity in cases where it could hardly be avoided—suspension systems and slender arches, for example. Even with the computer, nonlinear analyses have not been used extensively. They can be expensive and time consuming to make, and results can be difficult to interpret. But this situation is changing. In recent years, a large amount of research has been devoted to improving the efficiency of nonlinear methods. Also, the continuing revolution in computers is speeding up the computational process and reducing the cost of computation.

Interactive Computer Graphics—Some aspects of the role of interactive graphics in these developments are obvious. These, and others that are perhaps not so self-evident, will be listed below. First, the particular system used in the Cornell research will be described. The characteristics of the system that are of importance to the structural engineer should become apparent from later pictorial explanations.

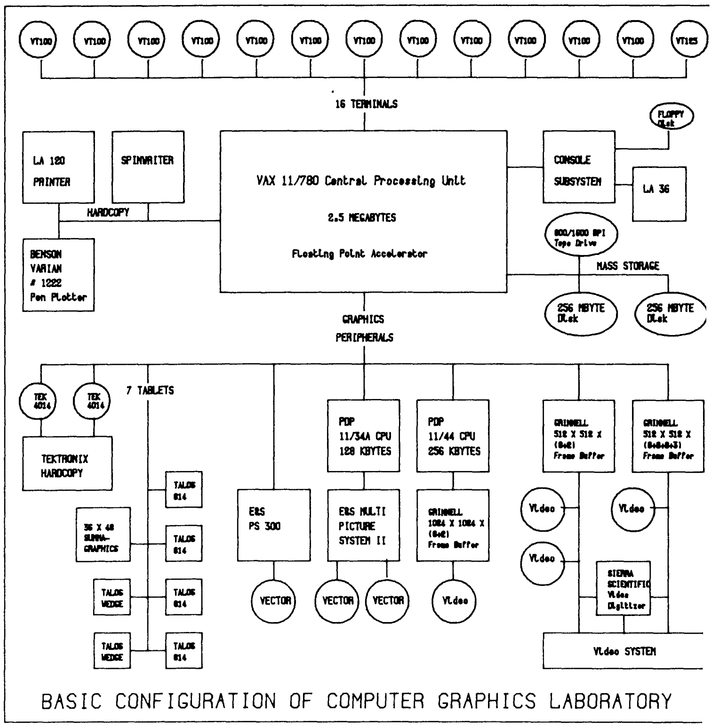

Fig. 1. Laboratory hardware configuration, Cornell University Laboratory of Computer Graphics

The configuration of Cornell's Laboratory of Computer Graphics is outlined in Fig. 1. Of particular importance are the VAX 11/780 32 bit virtual memory minicomputer which serves as the central processing unit for the laboratory, the Evans and Sutherland fast vector refresh graphics displays, the color raster displays, the digitizing tablets, the alpha-numeric terminals, and the printers, plotters and conventional hard-copy facilities.

Alphabetical, numerical and pictorial input, output and process stages can be displayed on the black/white and color devices. The dominant characteristic of a refresh graphics display is that the displayed image is recreated continuously in fractions of a second. Thus the perceived image is dynamic, permitting the realistic portrayal of motion.

The operator controls the system through the keyboard of the terminal, or directly through the digitizing tablet as indicated in Fig. 2, in which a user is seated at a tablet placed in front of a vector display scope. Movement of a stylus on the tablet is duplicated by a small cross, or cursor, displayed on the screen. Thus a particular area of the screen can be identified by simply "pointing" to it. Through the manual operation of the stylus on the tablet, commands may be issued and the flow of the program controlled. Numerical data can be entered by displaying a small numerical keypad on the screen and designating digits, rather as one uses the keyboard of a pocket calculator. After using the alphanumeric terminal to log onto the system, almost all subsequent communication is through the digitizing tablet.

The response of such a system is immediate. A change in a display, for example the addition of a member, is ac-

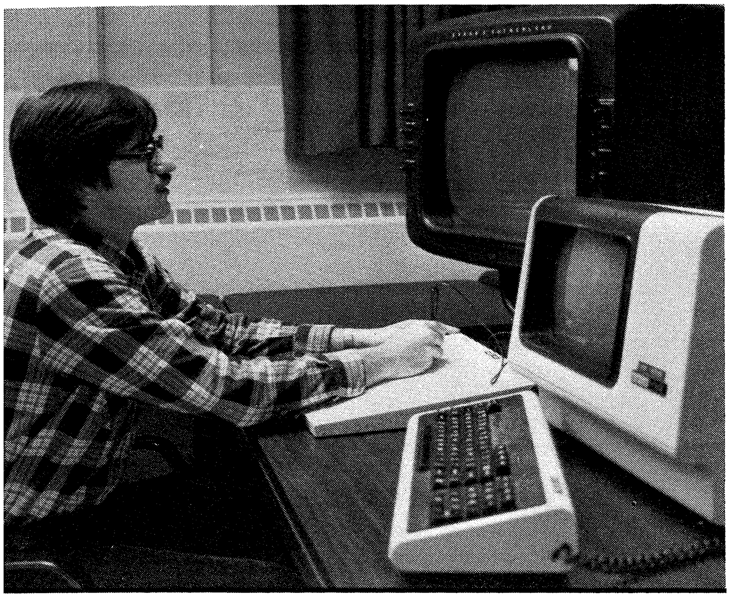

Fig. 2. Operator scans display scope, digitizing tablet and alphanumeric terminal.

complished in a small part of a second. Input is easy to make and to check. Monitoring and control of the progress of calculations is facilitated. This is particularly important in nonlinear or dynamic analysis, where it is often necessary to change load or time step size, or to ignore a portion of an analysis and to redo it or to restart it from a prior point. The advantages of graphic displays of structural response features are obvious. Perhaps not so obvious is the fact that an interactive graphics system can be the most user friendly of all computer-aided design systems devised to date.

Research and Development—The project to be described was started in 1979 as a joint undertaking of Cornell's Department of Structural Engineering and its Laboratory of Computer Graphics.

For research in structural engineering, it was decided at the beginning to address some of the important outstanding problems in the static and dynamic nonlinear analysis of three-dimensional framed structures considered most suitable to investigation through the medium of interactive computer graphics. References 5, 6, 7, 8, 9, 10 and 11 contain some of the findings of this research.

To apply the results of the research, it was decided to initiate development of computer-aided design systems for the static and earthquake design of steel framed structures. Progress in the static design system is described here.

CURRENT ANALYSIS/DESIGN SYSTEM

Any system of computer-aided design should attempt to satisfy the following principles:

1. Engineering design is a creative process. The engineer should be able to work in an environment in which the center of attention is the structure. The computer should be unobtrusive.
2. Analysis is an integral part of design. The engineer should have the capability of calling immediately upon either analysis routines or design sequences. He should be able to switch from one to the other and to restart, redo or enter any place of the process in almost any order.
3. Input requirements vary. Most data can best be entered by the engineer in some direct way as they are required.
4. Output requirements vary. The engineer should be able to select readily only those derived results important to a particular job.
5. All data should be easy to read, interpret and check.
6. The level of computation required varies from job to job. The engineer should have at his command analysis and design procedures of various levels of sophistication or rigor.

Since the system is a graphical one, the best way to convey impressions of what it can do, what its limitations are, and whether or not it measures up to these principles, is through pictures. This will be done after outlining the system's program structure and components. The contents of each are listed in Fig. 4. Briefly, anything required for creation of a new structure or modification of an existing one is defined as *preprocessing*. Analytical tools and design equations are *processing*. Any scheme for graphical display

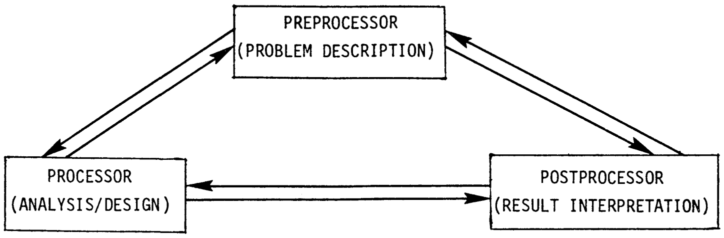

Fig. 3. Program components

PREPROCESSOR (PROBLEM DESCRIPTION)	PROCESSOR (ANALYSIS/DESIGN)	POST PROCESSOR (RESULT INTERPRETATION)
GEOMETRY DEFINITION BOUNDARY CONDITIONS MEMBER PROPERTIES LOADS	3D ANALYSIS FIRST ORDER ELASTIC SECOND ORDER ELASTIC FIRST ORDER ELASTIC-PLASTIC SECOND ORDER ELASTIC-PLASTIC LOAD COMBINATIONS DESIGN EQUATIONS TENSION COMPRESSION SHEAR BENDING-COMPRESSION INTERACTION EFFECTIVE LENGTHS MEMBER REDESIGN	LOAD-DISPLACEMENT DIAGRAMS DEFLECTED SHAPES MODE SHAPES INTERNAL FORCE DIAGRAMS (COLOR) HARD COPY

Fig. 4. Contents of components

of results and for obtaining printed or plotted output is defined as *postprocessing*.

These definitions are useful for descriptive purposes, but they are not rigidly separated blocks in the program. All are served by a common database and operations in more than one component may take place simultaneously or in rapid sequence. For example, the progress of a nonlinear analysis may be monitored by dynamic displays that trace a changing deflected shape, component of displacement versus load or component of internal force versus load. Also, after making a preliminary analysis (*processing*), one may want to display several deflection diagrams (*postprocessing*). If the deflections are acceptable, all members may then be subjected to a series of design checks (*processing*). Review of these might indicate the desirability of changing a particular support condition, which would require editing the structure (*preprocessing*) prior to making the next analysis (*processing*). Tacking back and forth this way, which is frequent in design, is facilitated by the interactive controls provided.

It is up to the user to determine how best to use the capability afforded by the system. It can be used conventionally by extracting two-dimensional subassemblages from a proposed frame, analyzing them by linear elastic theory, checking each member for compliance with a specification, and refining as desired. Or it can be used unconventionally by subjecting a proposed three-dimensional frame to a full geometric and material nonlinear analysis to collapse, with the user then judging—without performing any specification checks—whether adequate strength and stiffness have been demonstrated. All levels of practice between these two extremes are possible.

The capabilities of the Cornell system as it exists (1982) will be illustrated through three series of graphical displays. The first series (Figs. 5–18) demonstrates the interactive definition of a three-dimensional building. The second (Figs. 19–28) shows some of the aspects of a limit states design of the members of this frame. And the third (Figs. 29–37), shows a nonlinear analysis and design review of one planar bent of the same structure. Each series contains additional pictures to illustrate other features of the system.

Series 1. DEFINITION OF A THREE-DIMENSIONAL FRAME

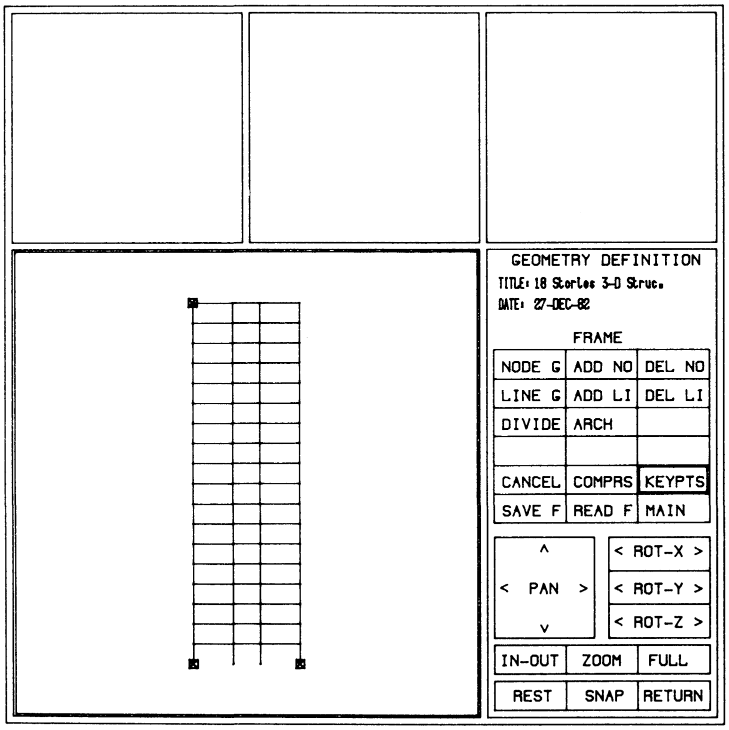
GEOMETRY DEFINITION
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Fig. 5. Basic frame geometry.
Basic plane frame component of building is defined by specifying bay spacing and story height. Three key points are identified for use in attaching this frame to adjacent ones. Three-dimensional sub-frames may also be used as building blocks. Irregular frameworks are created by either modifying these frames or line-by-line.

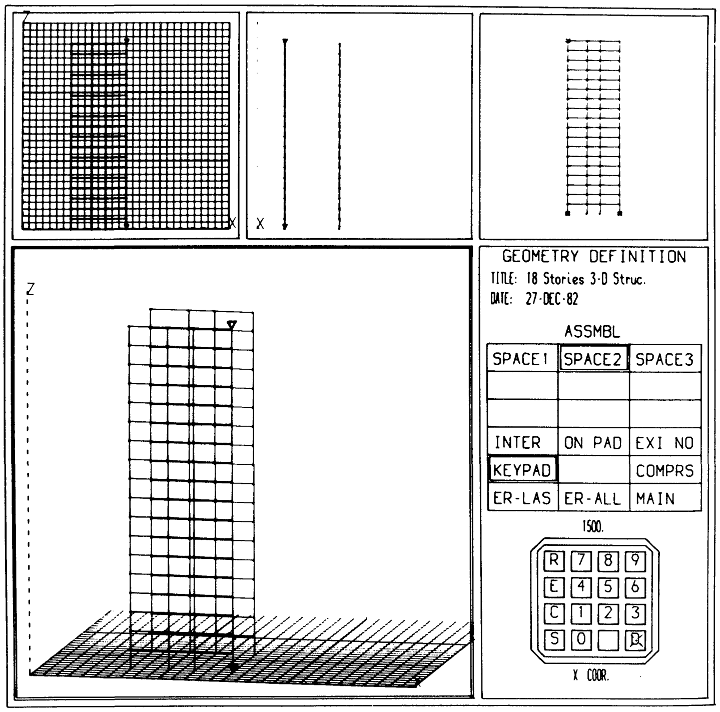
GEOMETRY DEFINITION
TITLE: 18 Stories 3-D Struc.
DATE: 27-DEC-82

Fig. 6. Frame assembling.
Subframes may be positioned in global structure coordinate system by using digitizing tablet to assign interactively key points to proper locations. Global coordinates of key points may also be specified by using numerical keypad shown in lower right corner.

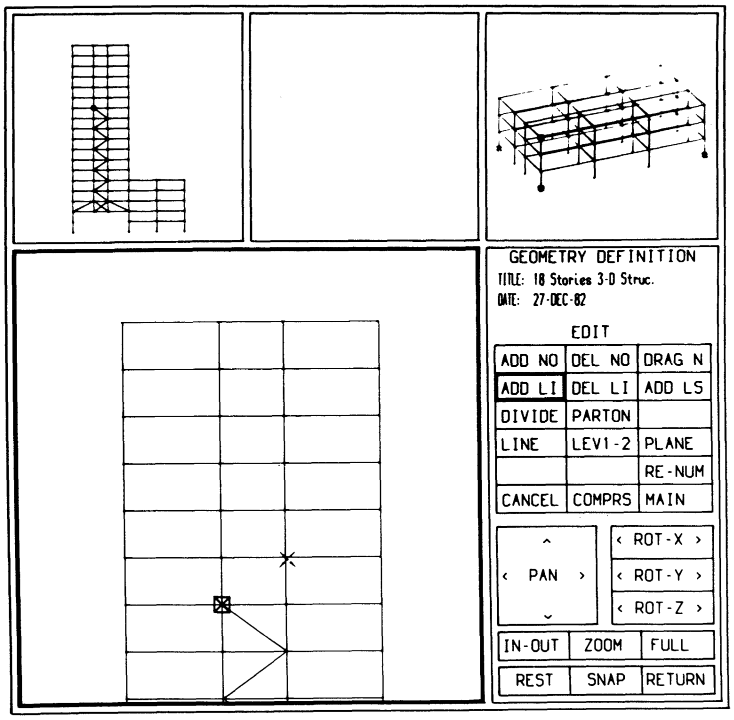

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Fig. 7. Structure editing.
Structure can be edited by adding or deleting lines or nodes. Enlarged views, sectional views or isolated views (shown) of selected frames can be used to facilitate editing of large systems. View of three-dimensional subframe defined in prior step retained in upper right viewport.

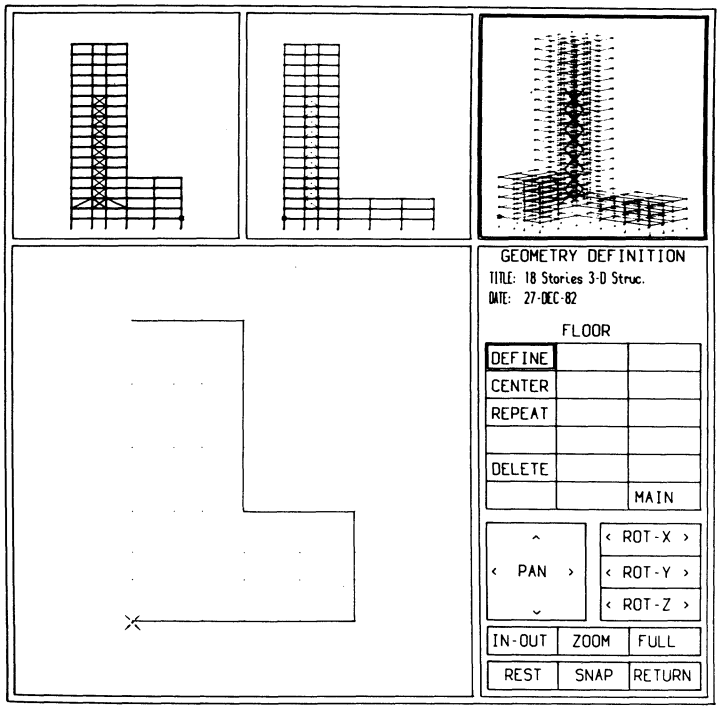

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Fig. 8. Floor definition.
Complete geometry has been defined. Three views retained in upper viewports for reference. When floor is assumed to be rigid in plane, as in this example, it is necessary to define floor plan. This is done by interactively defining one or more polygons by connecting nodes at selected level. Program creates a three-degree-of-freedom node (horizontal displacements and in-plane rotation) at mass center of floor.

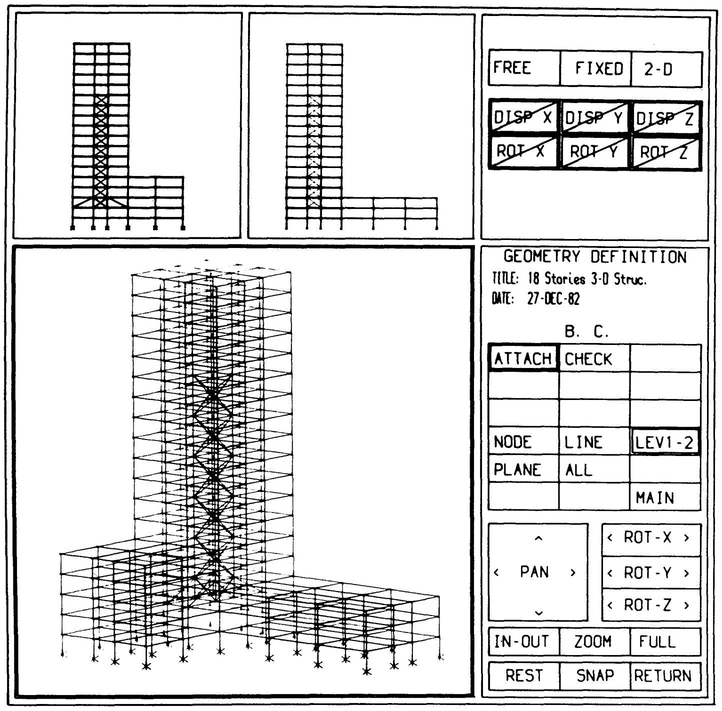

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Fig. 9. Boundary conditions.
Fixity condition of nodes is specified with respect to global coordinate system. Table with entry for each degree of freedom is displayed to indicate permissible range of boundary conditions. Conditions desired are selected by pointing to each. By then pointing to a node or group of nodes it is possible to assign at once selected boundary condition to all nodes in segment, level, or plane.

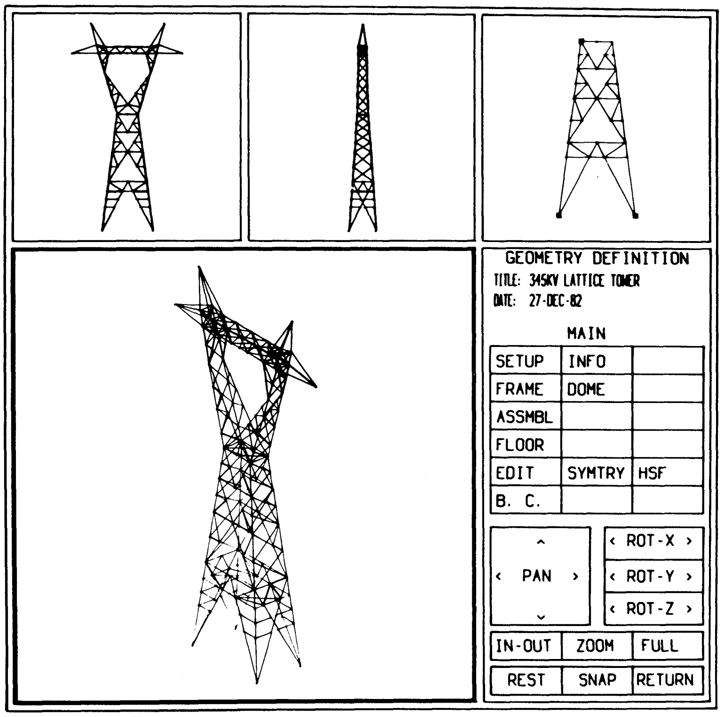

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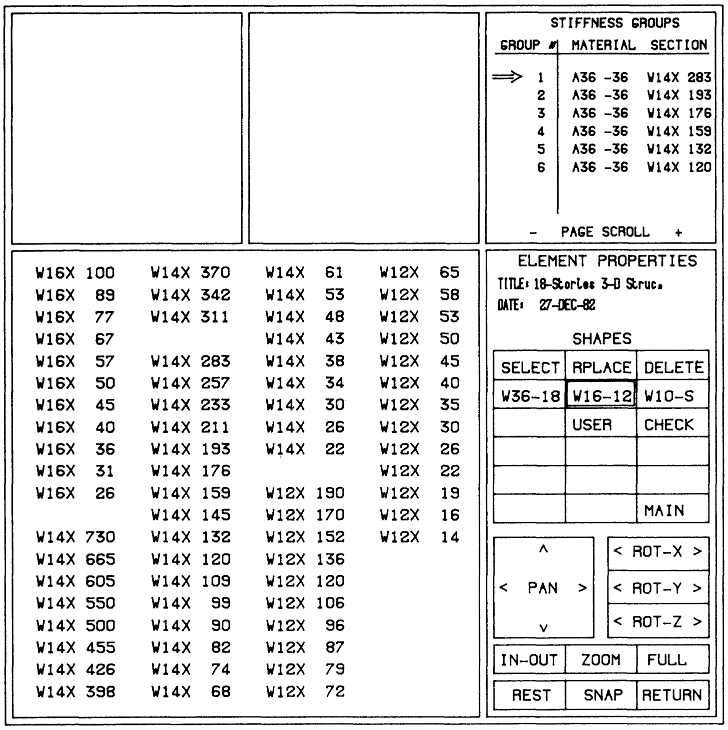
Fig. 10. Transmission tower.
This is example of general space frame. Each plane can be identified as a frame. Assembling procedure previously described was used to generate the basic geometry. It was necessary to specify directly coordinates of some nodes. Line elements were added by connecting lines between these nodes.



GROUP #	MATERIAL	SECTION
⇒ 1	A36 -36	W14X 283
2	A36 -36	W14X 193
3	A36 -36	W14X 176
4	A36 -36	W14X 159
5	A36 -36	W14X 132
6	A36 -36	W14X 120

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DATE: 27-DEC-82

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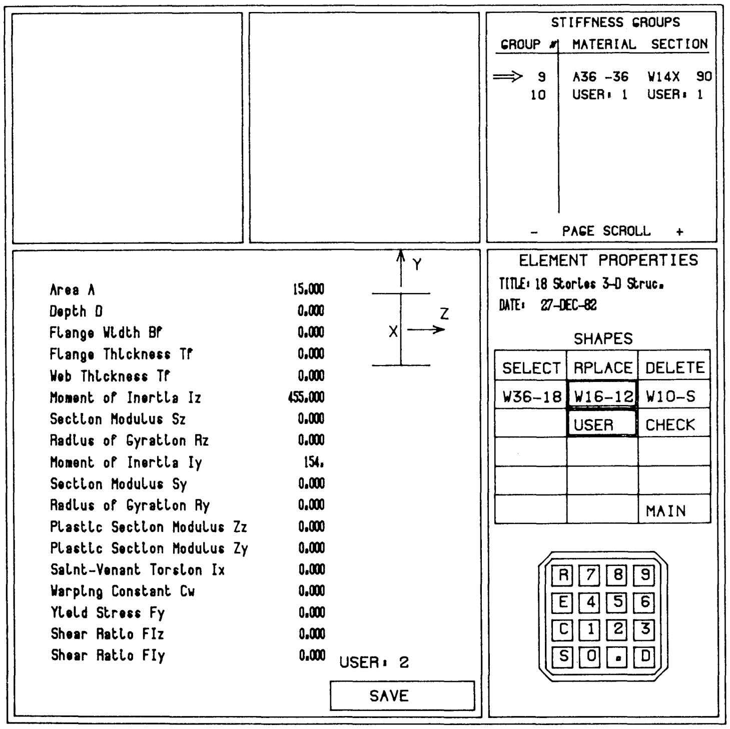
W16X 100   W14X 370   W14X  61   W12X  65
W16X  89   W14X 342   W14X  53   W12X  58
W16X  77   W14X 311   W14X  48   W12X  53
W16X  67              W14X  43   W12X  50
W16X  57   W14X 283   W14X  38   W12X  45
W16X  50   W14X 257   W14X  34   W12X  40
W16X  45   W14X 233   W14X  30   W12X  35
W16X  40   W14X 211   W14X  26   W12X  30
W16X  36   W14X 193   W14X  22   W12X  26
W16X  31   W14X 176              W12X  22
W16X  26   W14X 159   W12X 190   W12X  19
           W14X 145   W12X 170   W12X  16
W14X 730   W14X 132   W12X 152   W12X  14
W14X 665   W14X 120   W12X 136
W14X 605   W14X 109   W12X 120
W14X 550   W14X  99   W12X 106
W14X 500   W14X  90   W12X  96
W14X 455   W14X  82   W12X  87
W14X 426   W14X  74   W12X  79
W14X 398   W14X  68   W12X  72
```

Fig. 11. Active section table.
Sections to be used in problem are selected from tables of wide-flange sections. Properties of all common sections are in database. It is also possible to define properties of an entry in table (user defined section). For a particular problem list of sections is made by combining sections from table and any defined by user.



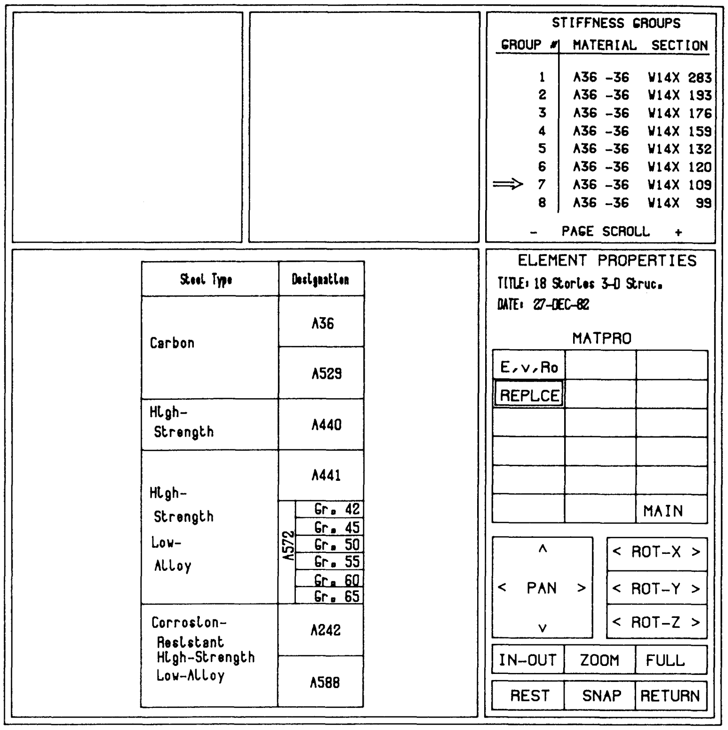
GROUP #	MATERIAL	SECTION
⇒ 9	A36 -36	W14X 90
10	USER: 1	USER: 1

TITLE: 18 Stories 3-D Struc.
DATE: 27-DEC-82

Area A	15.000
Depth D	0.000
Flange Width Bf	0.000
Flange Thickness Tf	0.000
Web Thickness Tf	0.000
Moment of Inertia Iz	455.000
Section Modulus Sz	0.000
Radius of Gyration Rz	0.000
Moment of Inertia Iy	154.
Section Modulus Sy	0.000
Radius of Gyration Ry	0.000
Plastic Section Modulus Zz	0.000
Plastic Section Modulus Zy	0.000
Saint-Venant Torsion Ix	0.000
Warping Constant Cw	0.000
Yield Stress Fy	0.000
Shear Ratio FIz	0.000
Shear Ratio FIy	0.000

USER: 2

Fig. 12. User defined sections.
List of sectional properties that can be input is displayed in main viewport. To input section property, corresponding display line must be pointed to. Message is typed indicating property to be defined. Keypad is then used to give desired value. When necessary properties are defined, section is added to list.



GROUP #	MATERIAL	SECTION
1	A36 -36	W14X 283
2	A36 -36	W14X 193
3	A36 -36	W14X 176
4	A36 -36	W14X 159
5	A36 -36	W14X 132
6	A36 -36	W14X 120
⇒ 7	A36 -36	W14X 109
8	A36 -36	W14X 99

TITLE: 18 Stories 3-D Struc.
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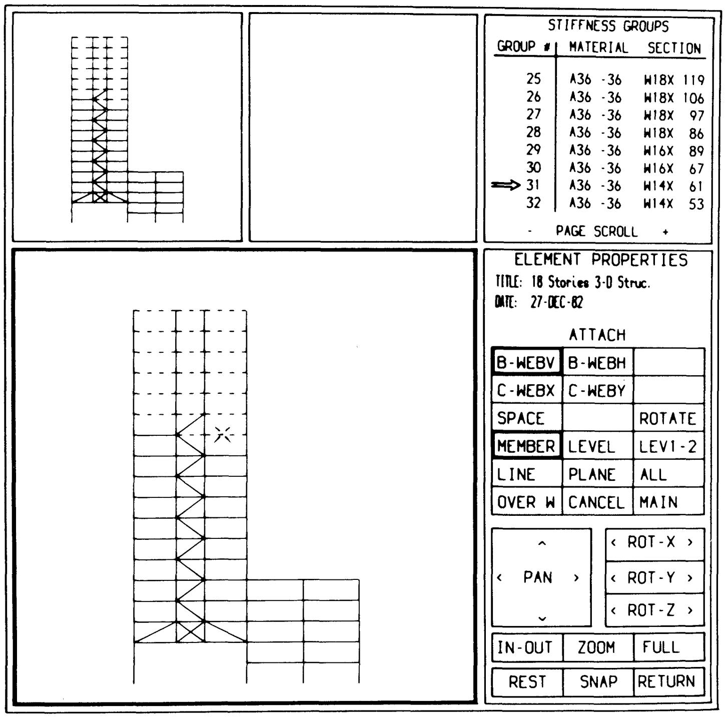
Steel Type	Designation	
Carbon	A36	
	A529	
High-Strength	A440	
High-Strength Low-Alloy	A441	
	A572	Gr. 42
		Gr. 45
		Gr. 50
		Gr. 55
		Gr. 60
		Gr. 65
Corrosion-Resistant High-Strength Low-Alloy	A242	
	A588	

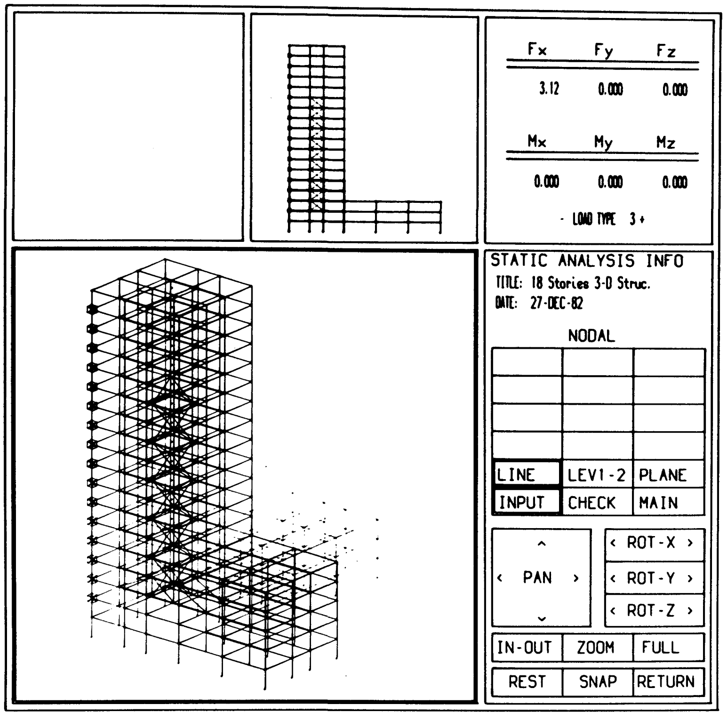
Fig. 13. Type of steel.
A 36 steel is assumed unless another type is selected from display. Program will check availability of section in selected steel type.



GROUP #	MATERIAL	SECTION
25	A36 -36	W18X 119
26	A36 -36	W18X 106
27	A36 -36	W18X 97
28	A36 -36	W18X 86
29	A36 -36	W16X 89
30	A36 -36	W16X 67
⇒ 31	A36 -36	W14X 61
32	A36 -36	W14X 53

TITLE: 18 Stories 3-D Struc.
DATE: 27-DEC-82

Fig. 14. Properties assignment.
Orientation of web plane (minor axis) and member properties are specified at same time. Active section for assignment is indicated by arrow next to list number. Properties of active section are assigned to members simply by pointing to members. For general case of orientation, specification of third node is necessary.



Fx Fy Fz

3.12 0.000 0.000

Mx My Mz

0.000 0.000 0.000

- LOAD TYPE 3 +

STATIC ANALYSIS INFO

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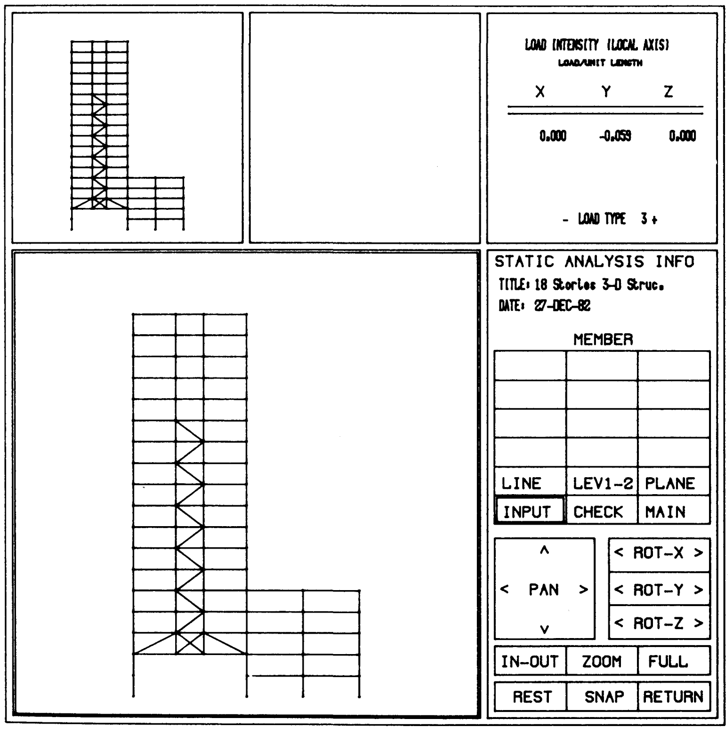
NODAL

Fig. 15. Nodal loads.
Load at node is specified by three components of force and moment with reference to global axes. Numerical values are entered by keypad displayed on screen. After all components are specified, keypad is replaced by structure position control module. Nodes or group of nodes subjected to load are located in convenient view and loads assigned by pointing.



LOAD INTENSITY (LOCAL AXIS)
LOAD/UNIT LENGTH

X Y Z

0.000 -0.059 0.000

- LOAD TYPE 3 +

STATIC ANALYSIS INFO

TITLE: 18 Stories 3-D Struc.

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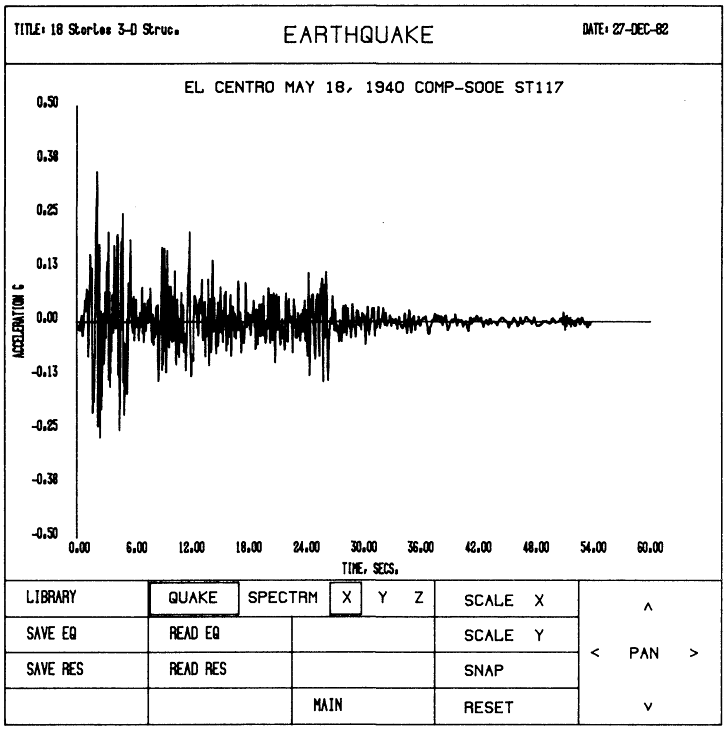
MEMBER

Fig. 16. Member loads.
Three components of uniformly distributed loads along members are specified in similar way. Subroutine then computes equivalent nodal loads for use in analysis.



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EARTHQUAKE

DATE: 27-DEC-82

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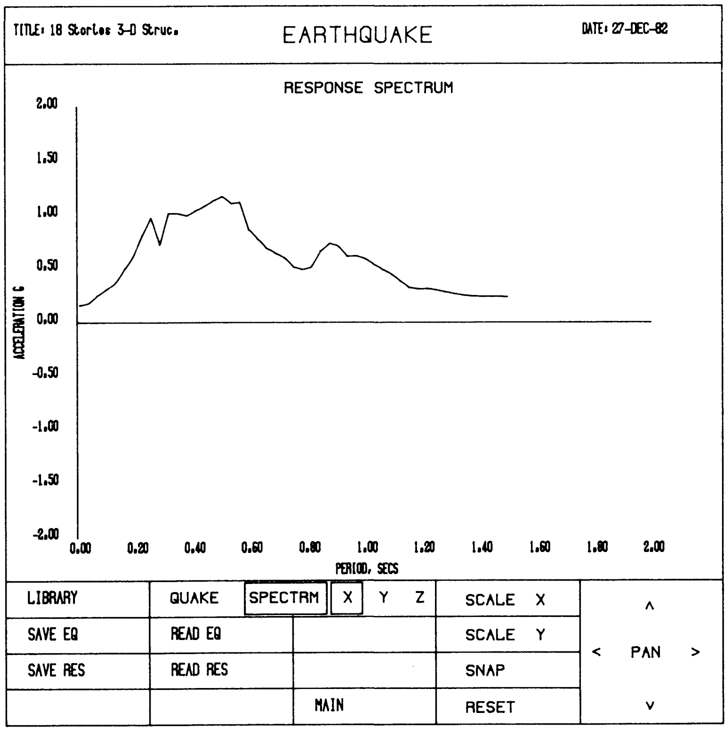
Fig. 17. Earthquake loads.
Several alternatives for specifying earthquake loads are available. One is to select from library file of accelerograms of typical earthquakes. Selected function is assigned to active earthquake direction. There are extensive editing capabilities for modifying earthquake forcing function.



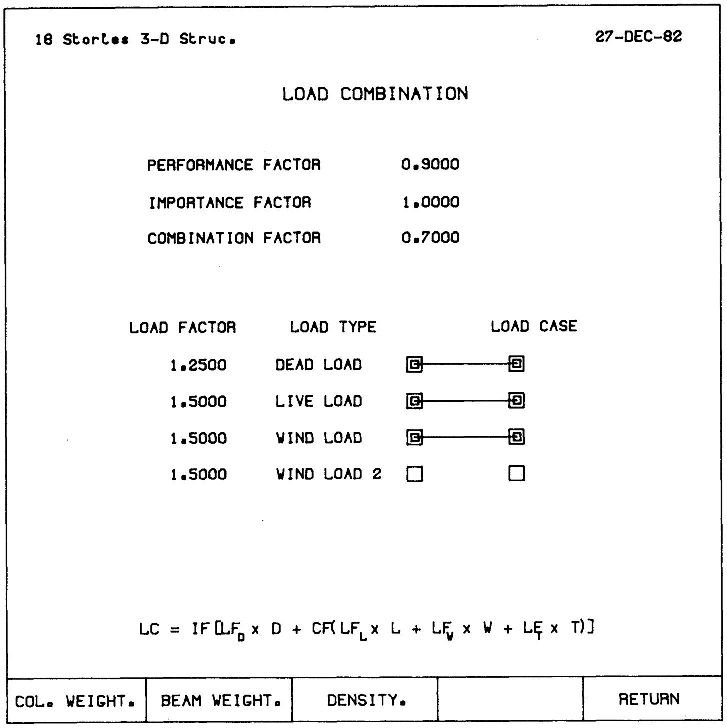
TITLE: 18 Stories 3-D Struc.

EARTHQUAKE

DATE: 27-DEC-82

RESPONSE SPECTRUM

Fig. 18. Response spectrum.
Response spectrum curves are defined in similar way. They may also be generated from components of accelerogram.



18 Stories 3-D Struc. 27-DEC-82

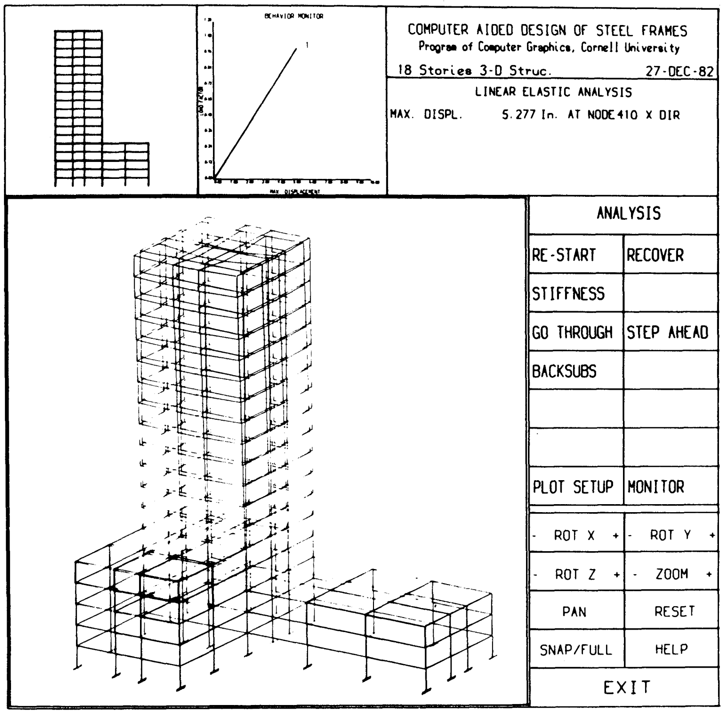
LOAD COMBINATION

PERFORMANCE FACTOR 0.9000
IMPORTANCE FACTOR 1.0000
COMBINATION FACTOR 0.7000

LOAD FACTOR	LOAD TYPE		LOAD CASE
1.2500	DEAD LOAD	☒	☒
1.5000	LIVE LOAD	☒	☒
1.5000	WIND LOAD	☒	☒
1.5000	WIND LOAD 2	☐	☐

$$LC = IF[LF_D \times D + CF(LF_L \times L + LF_W \times W + LF_T \times T)]$$

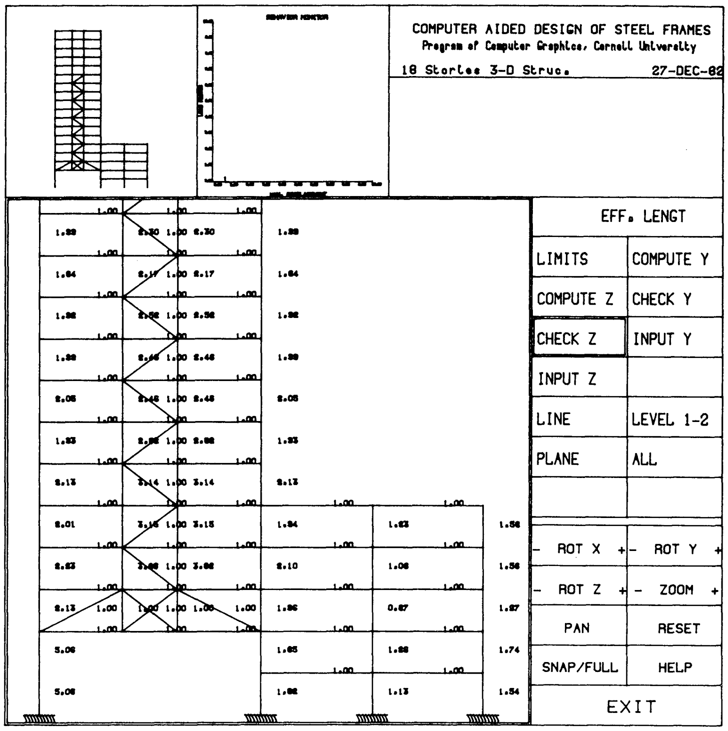
Fig. 19. Define limit state.
Limits states and load combinations can be defined. In preprocessor, different load types are specified. End result of operation shown is single combined load vector formed by multiplying different load types by their associated load factors and load combination factors, adding these quantities, and multiplying total by importance factor. Canadian Standard Association Limits States Design Equation is shown for reference. Resulting combined load vector is called "load case."



COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
18 Stories 3-D Struc. 27-DEC-82

LINEAR ELASTIC ANALYSIS
MAX. DISPL. 5.277 In. AT NODE410 X DIR

Fig. 20. Perform linear elastic analysis.
For each iteration, linear elastic analysis is performed. As soon as results are available, deflected shape of structure is drawn and load deflection diagram for preselected degree of freedom displayed. Maximum displacement is reported. In nonlinear analysis, these tools are useful in making decision to continue or to stop analysis.



COMPUTER AIDED DESIGN OF STEEL FRAMES
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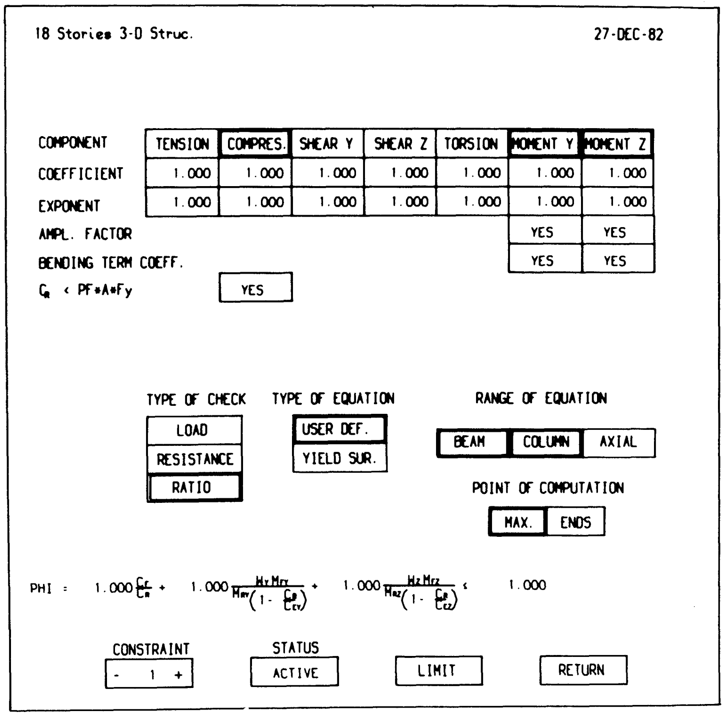
Fig. 21. Effective length factors.
Effective length factors to be used in design can either be computed from an eigenvalue analysis for given load distribution or specified by user. Computed values for columns of portion of structure are shown. Beam effective lengths have been assigned by user. Buckling modes can also be displayed.



18 Stories 3-D Struc. 27-DEC-82

COMPONENT	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
AMPL. FACTOR						YES	YES
BENDING TERM COEFF.						YES	YES

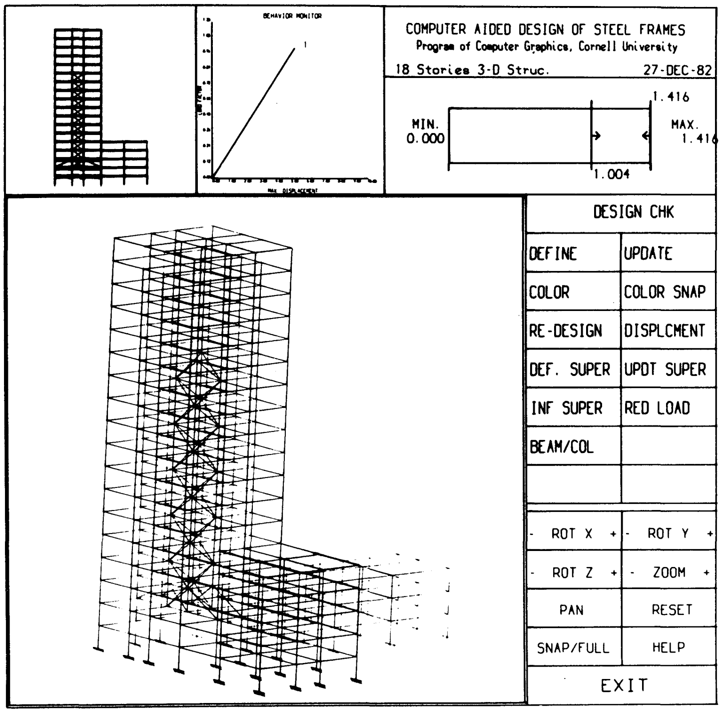
$C_f < PF*A*Fy$ YES

TYPE OF CHECK: LOAD, RESISTANCE, RATIO (selected: RATIO)
TYPE OF EQUATION: USER DEF., YIELD SUR. (selected: USER DEF.)
RANGE OF EQUATION: BEAM, COLUMN, AXIAL (selected: BEAM, COLUMN)
POINT OF COMPUTATION: MAX., ENDS (selected: MAX.)

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

CONSTRAINT - 1 +
STATUS ACTIVE

Fig. 22. Define design equations.
Specification requirements for tension, compression, shear and combined effects can be defined. CSA Limit State Design axial compression and bending interaction equation is shown. Other equations may be defined. In general, each term can be multiplied by factor, and each term can be raised to any specified power. More than one design constraint can be specified.



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COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
18 Stories 3-D Struc.                    27-DEC-82
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Fig. 23. Design evaluation.
With results of analysis available, active design equation is evaluated for each member at its critical location. After interactively defining range of values, blinking lines indicate members for which sum of interaction equation terms is within range. This permits identification of critical members in structure.

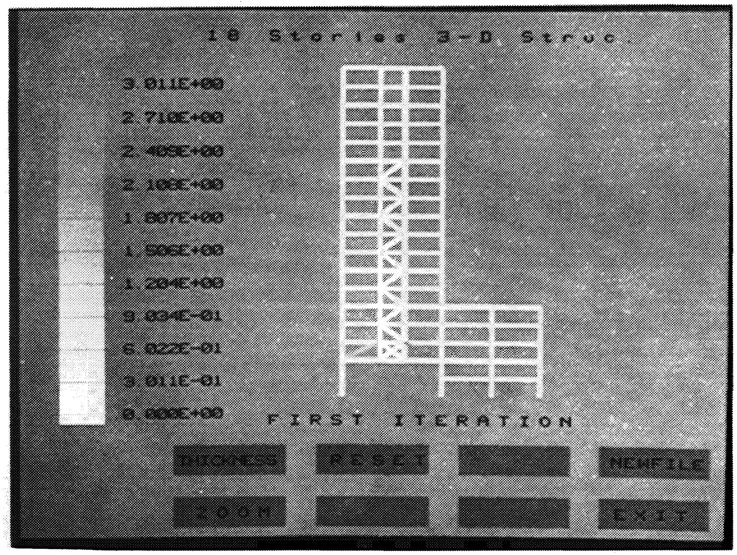
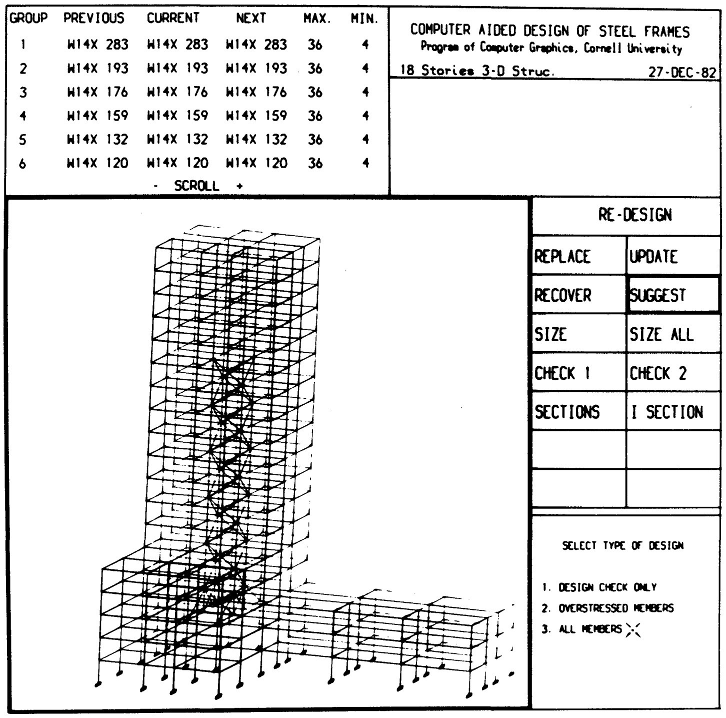


Fig. 24. Design evaluation (color display).
A color, graded from yellow to red, is assigned to each member according to value of design equation reviewed. Light yellow corresponds to current minimum value of design equation and deep red to current maximum value. This permits evaluation of design of whole structure or major part of it by comparing relative colors and by noting range of values. In this display of another load case, bright red indicates two members are grossly underdesigned, and light yellow a number overdesigned at this stage.



```
GROUP  PREVIOUS   CURRENT    NEXT       MAX.  MIN.
 1     W14X 283   W14X 283   W14X 283   36     4
 2     W14X 193   W14X 193   W14X 193   36     4
 3     W14X 176   W14X 176   W14X 176   36     4
 4     W14X 159   W14X 159   W14X 159   36     4
 5     W14X 132   W14X 132   W14X 132   36     4
 6     W14X 120   W14X 120   W14X 120   36     4
                  -  SCROLL  +

COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
18 Stories 3-D Struc.                    27-DEC-82
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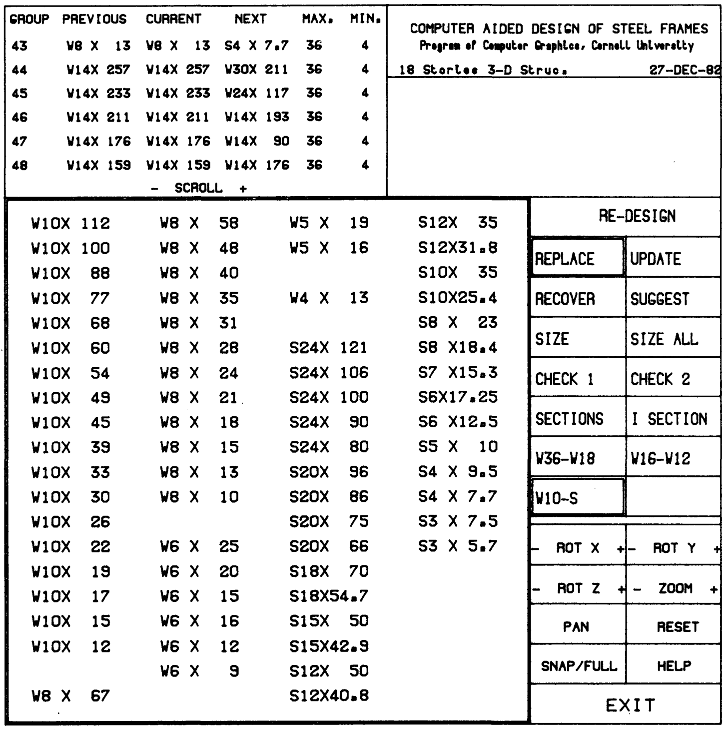
Fig. 25. Automatic redesign.
Algorithm has been implemented that will select lightest section that satisfies design equations. Limits can be imposed on size of member to be selected, and member grouping can be specified to reduce number of different member sizes.



```
GROUP  PREVIOUS   CURRENT    NEXT       MAX.  MIN.
43     W8 X  13   W8 X  13   S4 X 7.7   36     4
44     W14X 257   W14X 257   W30X 211   36     4
45     W14X 233   W14X 233   W24X 117   36     4
46     W14X 211   W14X 211   W14X 193   36     4
47     W14X 176   W14X 176   W14X  90   36     4
48     W14X 159   W14X 159   W14X 176   36     4
                  -  SCROLL  +

COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
18 Stories 3-D Struc.                    27-DEC-82

  W10X 112     W8 X  58     W5 X  19     S12X  35
  W10X 100     W8 X  48     W5 X  16     S12X31.8
  W10X  88     W8 X  40                  S10X  35
  W10X  77     W8 X  35     W4 X  13     S10X25.4
  W10X  68     W8 X  31                  S8 X  23
  W10X  60     W8 X  28     S24X 121     S8 X18.4
  W10X  54     W8 X  24     S24X 106     S7 X15.3
  W10X  49     W8 X  21     S24X 100     S6X17.25
  W10X  45     W8 X  18     S24X  90     S6 X12.5
  W10X  39     W8 X  15     S24X  80     S5 X  10
  W10X  33     W8 X  13     S20X  96     S4 X 9.5
  W10X  30     W8 X  10     S20X  86     S4 X 7.7
  W10X  26                  S20X  75     S3 X 7.5
  W10X  22     W6 X  25     S20X  66     S3 X 5.7
  W10X  19     W6 X  20     S18X  70
  W10X  17     W6 X  15     S18X54.7
  W10X  15     W6 X  16     S15X  50
  W10X  12     W6 X  12     S15X42.9
               W6 X   9     S12X  50
  W8 X  67                  S12X40.8
```

Fig. 26. Manual redesign.
Section suggested by automatic design procedure may not be available, or user may prefer another section. In this case, new sections can be selected from table to replace current sections.

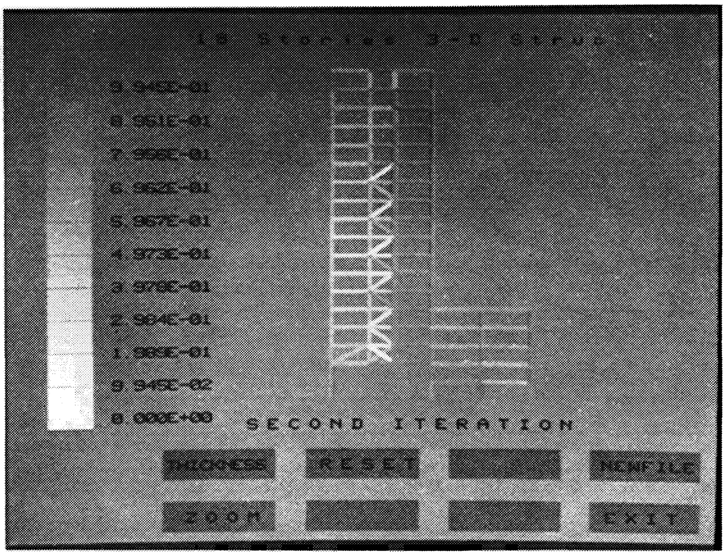


Fig. 27. Design evaluation (color display).
Comparison with Fig. 24 indicates succeeding iteration has produced structure more uniformly and efficiently stressed with respect to particular design equation being reviewed.

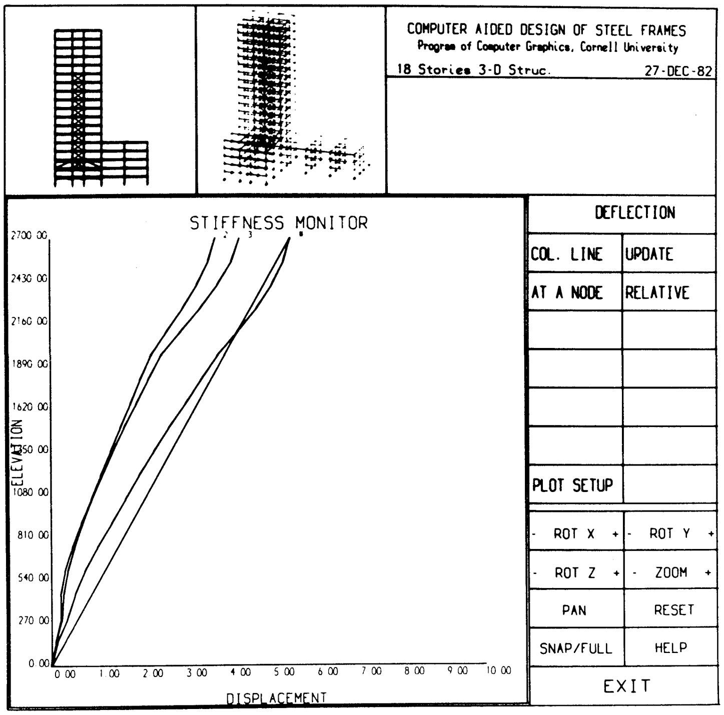
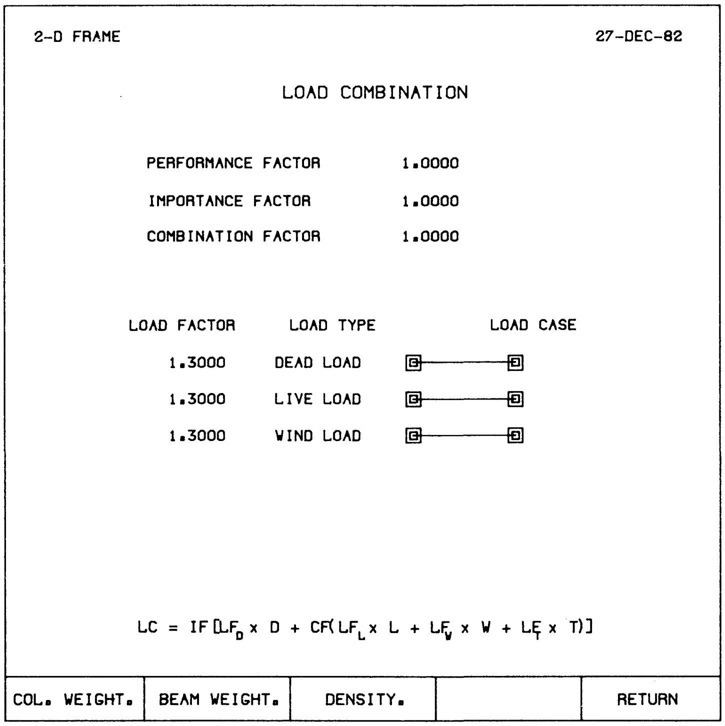


Fig. 28. Deflection along column line.
This section permits comparison of displacement of column line of structure with specified limit. Results for various design iterations can be compared in same graph. This helps in evaluation of effects of changes in member sizes on stiffness of structure.

Series 3. NONLINEAR ANALYSIS AND DESIGN OF A PLANAR FRAME


2-D FRAME 27-DEC-82

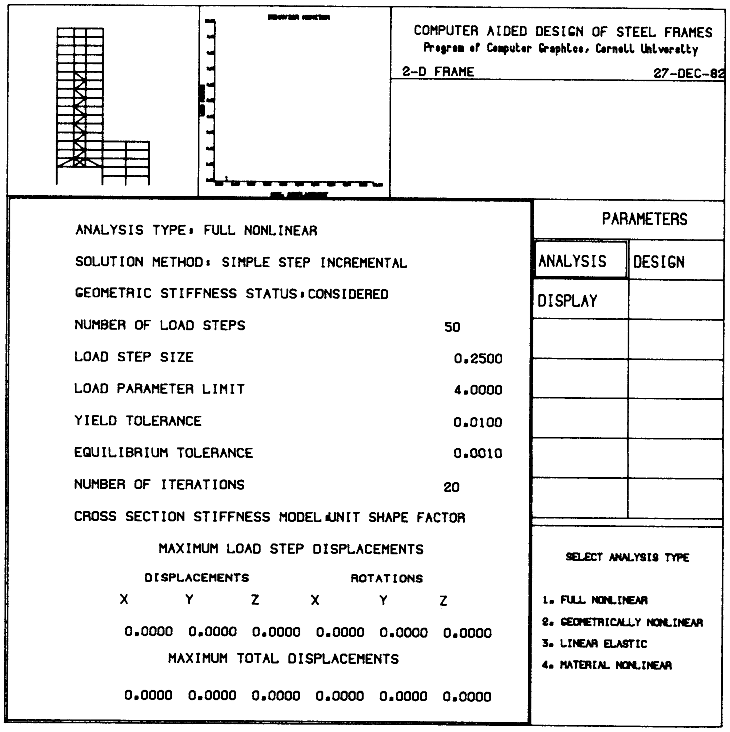
LOAD COMBINATION

PERFORMANCE FACTOR 1.0000
IMPORTANCE FACTOR 1.0000
COMBINATION FACTOR 1.0000

LOAD FACTOR	LOAD TYPE	LOAD CASE
1.3000	DEAD LOAD	⊟——⊟
1.3000	LIVE LOAD	⊟——⊟
1.3000	WIND LOAD	⊟——⊟

$$LC = IF[LF_D \times D + CF(LF_L \times L + LF_W \times W + LF_T \times T)]$$

Fig. 29. Define limit state.
Load condition considered is combination of gravity and wind load. Load factor of 1.3 is desired for combined effect of wind and gravity loads. Attempt will be made to apply this load to one planar bent of structure.



ANALYSIS TYPE: FULL NONLINEAR
SOLUTION METHOD: SIMPLE STEP INCREMENTAL
GEOMETRIC STIFFNESS STATUS: CONSIDERED

NUMBER OF LOAD STEPS	50
LOAD STEP SIZE	0.2500
LOAD PARAMETER LIMIT	4.0000
YIELD TOLERANCE	0.0100
EQUILIBRIUM TOLERANCE	0.0010
NUMBER OF ITERATIONS	20

CROSS SECTION STIFFNESS MODEL: UNIT SHAPE FACTOR

MAXIMUM LOAD STEP DISPLACEMENTS

DISPLACEMENTS			ROTATIONS		
X	Y	Z	X	Y	Z
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

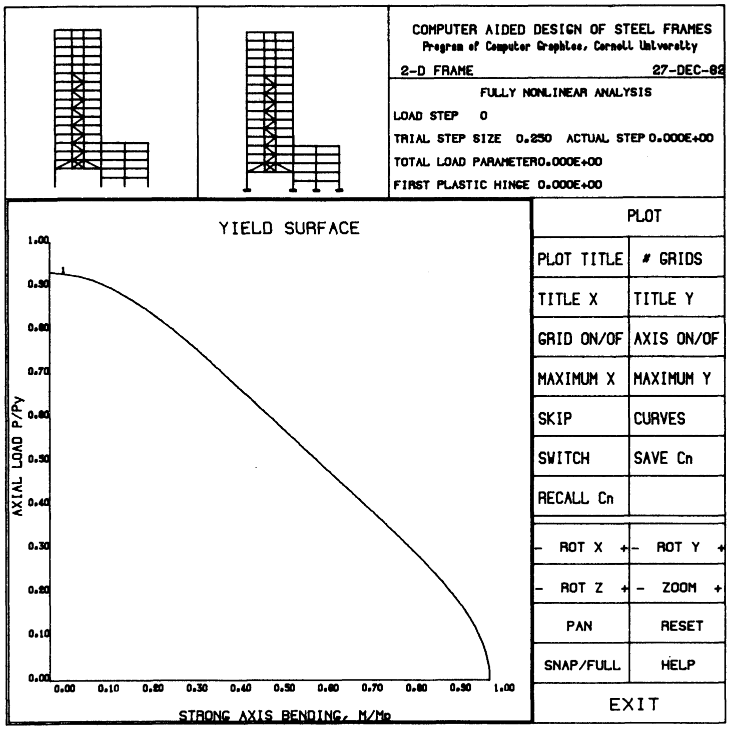
MAXIMUM TOTAL DISPLACEMENTS

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

SELECT ANALYSIS TYPE

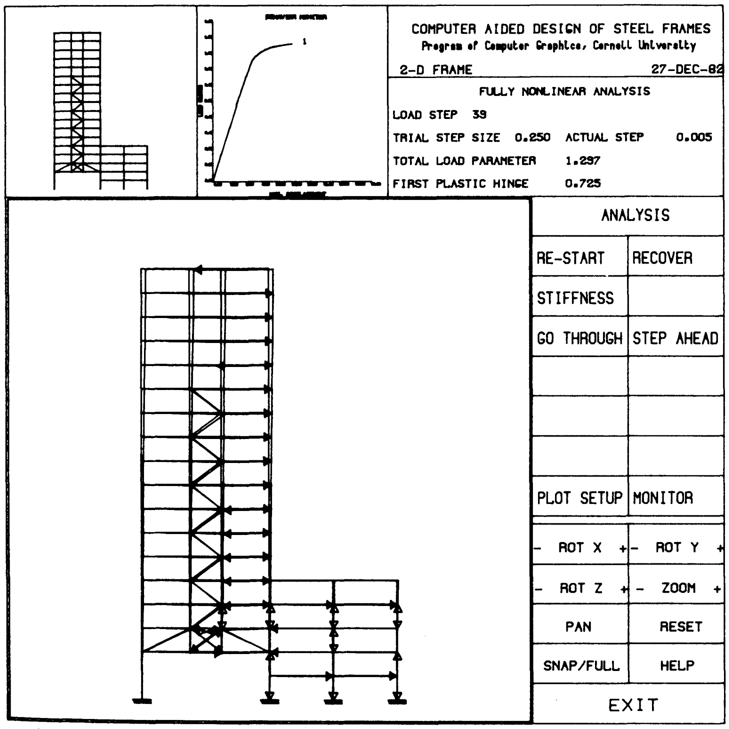
1. FULL NONLINEAR
2. GEOMETRICALLY NONLINEAR
3. LINEAR ELASTIC
4. MATERIAL NONLINEAR

Fig. 30. Define analysis parameters.
In this section, type of analysis to be performed and parameters controlling analysis are specified. In this case, analysis that includes both material and geometric nonlinearities will be performed.



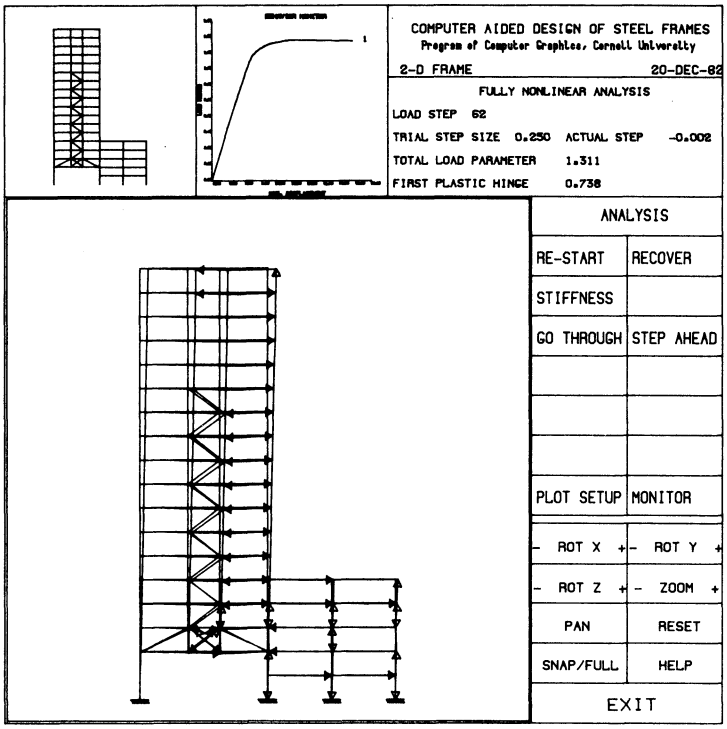
COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
2-D FRAME 27-DEC-82
FULLY NONLINEAR ANALYSIS
LOAD STEP 0
TRIAL STEP SIZE 0.250 ACTUAL STEP 0.000E+00
TOTAL LOAD PARAMETER0.000E+00
FIRST PLASTIC HINGE 0.000E+00

Fig. 31. Yield surface.
This is display of shape of yield surface for strong axis bending and axial loads. It is polynomial approximation of interaction diagram for wide-flange sections.[7,10]



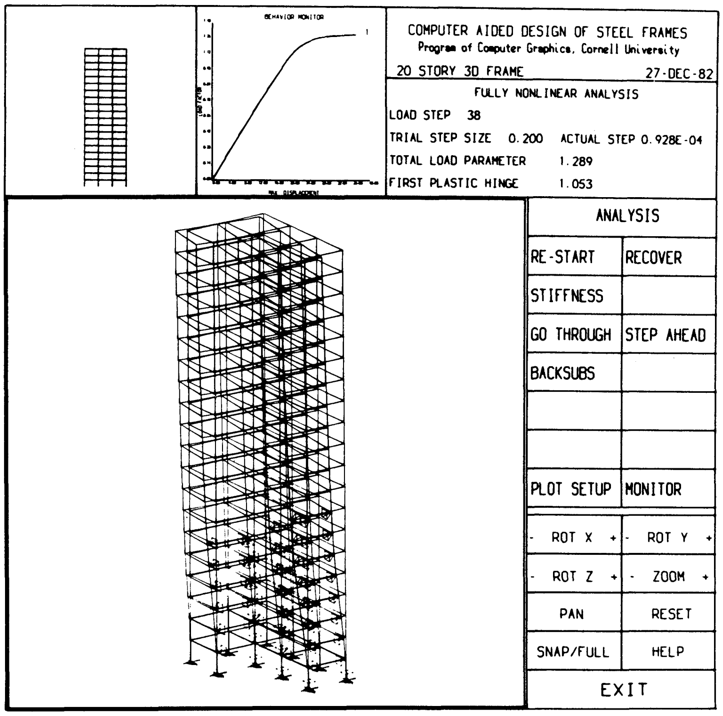
COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
2-D FRAME 27-DEC-82
FULLY NONLINEAR ANALYSIS
LOAD STEP 39
TRIAL STEP SIZE 0.250 ACTUAL STEP 0.005
TOTAL LOAD PARAMETER 1.297
FIRST PLASTIC HINGE 0.725

Fig. 32. Perform nonlinear analysis.
The step-by-step results of analysis are monitored. Conditions at limit load are shown in this view. Plastic hinges are indicated by small triangles. If structure does not perform as desired, it is possible to halt analysis at any time to redesign structure. No systematic way has been implemented to redesign a structure when nonlinear analyses are performed. The judgment of user in changing member properties is relied upon.



COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
2-D FRAME 20-DEC-82
FULLY NONLINEAR ANALYSIS
LOAD STEP 62
TRIAL STEP SIZE 0.250 ACTUAL STEP -0.002
TOTAL LOAD PARAMETER 1.311
FIRST PLASTIC HINGE 0.738

Fig. 33. Post collapse.
Nonlinear program is capable of tracing behavior into post-collapse range. After reaching peak, resistance is decreasing. Apparently high peak resistance obtained (total load parameter ≫1) can be attributed to fact that, for illustration, frame has been analyzed for in-plane effects only, whereas members were designed for biaxial bending.



COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
20 STORY 3D FRAME 27-DEC-82
FULLY NONLINEAR ANALYSIS
LOAD STEP 38
TRIAL STEP SIZE 0.200 ACTUAL STEP 0.928E-04
TOTAL LOAD PARAMETER 1.289
FIRST PLASTIC HINGE 1.053

Fig. 34. 20-story building.
This is example of building analyzed to collapse using full three-dimensional analysis that included consideration of both geometrical and material nonlinearities. Data on analysis are included in text to follow.

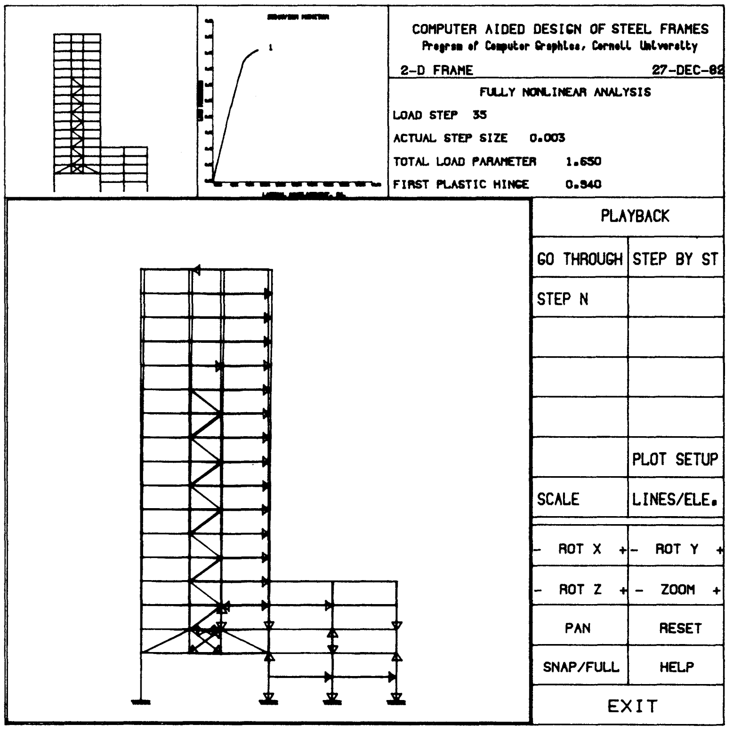

COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
2-D FRAME 27-DEC-82
FULLY NONLINEAR ANALYSIS
LOAD STEP 35
ACTUAL STEP SIZE 0.003
TOTAL LOAD PARAMETER 1.650
FIRST PLASTIC HINGE 0.940

Fig. 35. Playback of a completed analysis.
Deflected shape, location of plastic hinges, and analysis data are retained and may be displayed for any load step. Since no time is spent in analysis, displaying load steps one after other conveys dynamic picture of structure's behavior. One frame of playback of frame deflection is shown.

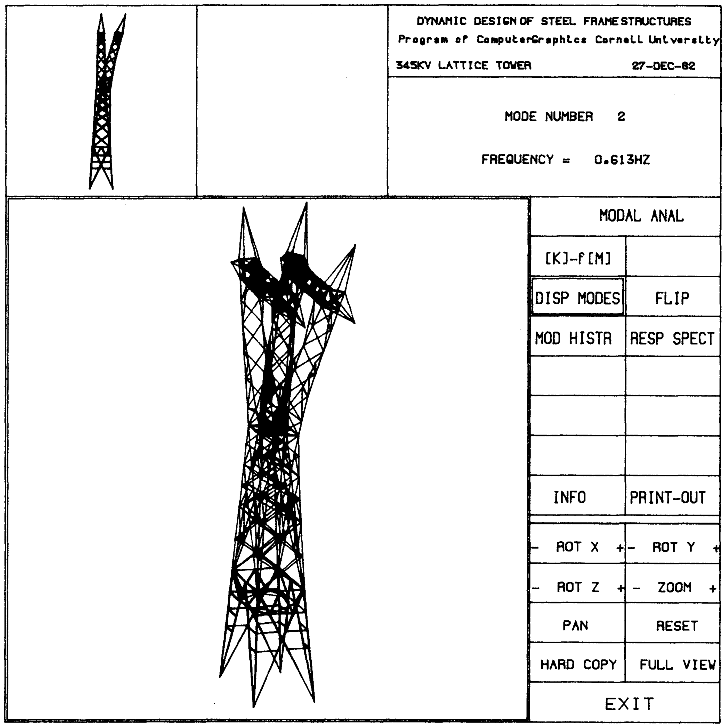

DYNAMIC DESIGN OF STEEL FRAME STRUCTURES
Program of ComputerGraphics Cornell University
345KV LATTICE TOWER 27-DEC-82
MODE NUMBER 2
FREQUENCY = 0.613HZ

Fig. 37. Mode shapes.
Vibration frequencies can be calculated and mode shapes displayed dynamically. Second mode of transmission tower is illustrated.

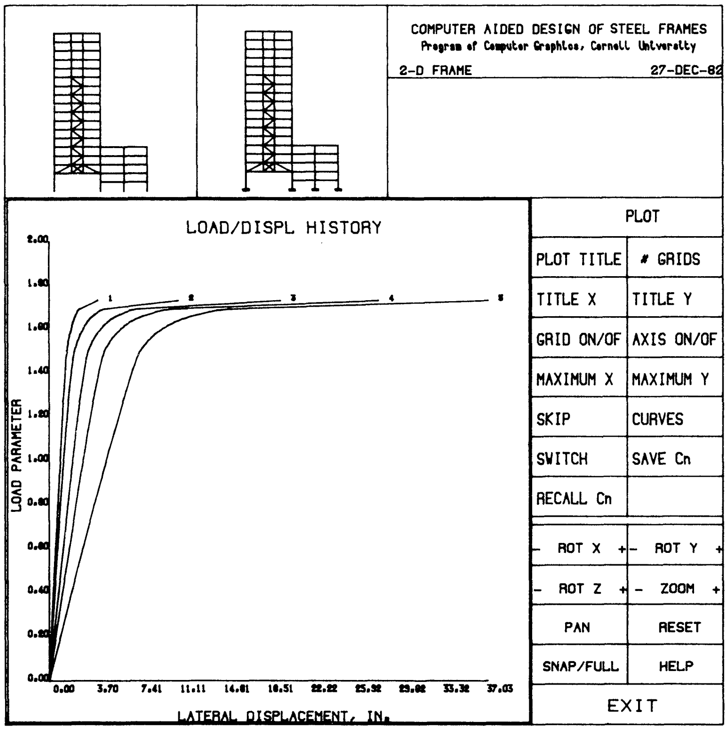

COMPUTER AIDED DESIGN OF STEEL FRAMES
Program of Computer Graphics, Cornell University
2-D FRAME 27-DEC-82

Fig. 36. History.
Load-deformation curve for degree of freedom in any member is one example of information that can be displayed in this section. Information can be obtained for more than one degree of freedom. This allows comparison of behavior of different degrees of freedom. Load deflection diagrams for five levels of frame are shown.

CAPABILITIES, LIMITATIONS, PROJECTIONS

The linear and nonlinear analysis programs used in the above examples are stiffness method programs employing a straight, prismatic, twelve-degree-of-freedom beam-column element. Full displacement compatibility of all degrees-of-freedom is assured. A geometric stiffness matrix is included and several incremental and iterative options are available for handling geometric nonlinearity. Material nonlinearity is incorporated by permitting plastic response of end cross sections under combinations of axial force and bending that satisfy a specified yield criterion. The criterion currently used is a continuous polynomial approximation of an interaction diagram for steel wide flange sections of medium weight. Elastic unloading of previously plastified cross sections is accommodated. Rigid connections are assumed. All programs have been written by Cornell graduate students for the interactive computer graphics system diagrammed in Fig. 1. Details of these and other features of the programs are presented in References 7, 8, 9 and 10.

The above references also contain the results of a number of numerical tests to which the programs have been subjected. The programs compare well with others in computational efficiency, accuracy and scope. As an example of the analysis of a framework of moderate size, the three-dimensional structure in Fig. 34 was analyzed to collapse in approximately 14 minutes, CPU time. The frame had 1,260° of freedom. Sixty-one plastic hinges formed during the analysis. Thirty-eight load steps were used in obtaining the response indicated in the figure. Comparison of analytical results with published data on tests of two-dimensional frames has also been good. Unfortunately, there is a dearth of experimental evidence on three-dimensional frame behavior. Developments in practical methods of linear and nonlinear three-dimensional analysis have been rapid in recent years, but if the promise of these methods is to be realized and if they are to be used with confidence they must have an underpinning of empirical support that is now missing. Of course this does not mean that one should avoid three-dimensional analysis as it now exists. No one has ever tested really large planar frames either, yet there is no reluctance to build major structures on the basis of a two-dimensional analysis. It is only suggested that caution be used in the application of any advanced analytical methods that do not have the benefit of laboratory corroboration or have not as yet had the test of extensive, successful use.

While the elastic and inelastic programs described should prove reliable and practical for the analysis and design of many two- and three-dimensional frameworks, they are still being refined. The most important practical limitations of the present system and some of the plans for further research and development follow.

1. At present, all connections are treated as rigid. A predecessor, two-dimensional program[5,11] included provisions for flexible and semi-rigid connections. Comparable three-dimensional capability is a routine extension that will be incorporated in the present programs in the near future. Research directed toward the development and inclusion of realistic panel zone effects will also be undertaken.
2. The beam-column element used is for members of bisymmetrical cross section. Further research is needed to develop a reliable unsymmetrical element.
3. Local buckling is not provided for. It is assumed all elements have compact cross sections. It is planned to add provisions for handling local buckling.
4. The design equations included to date adhere closely to the Canadian Limit States Design Specification.[2] This specification was selected because it reflects western hemisphere practice and because its use of a load and resistance factor format and forces rather than stresses appeared to be most suitable for incorporation in a computer-aided design system that addresses both service load conditions and ultimate resistance. Some of the 1978 AISC Specification provisions have also been incorporated. It should be possible to implement the basic provisions of the anticipated AISC LRFD Specification without difficulty.
5. SSRC Technical Memorandum No. 5[4] states, "Although the maximum strength of frames and members and the maximum strength of component members are interdependent, it is recognized that in many structures it is not possible to take this interdependence into account rigorously." Therefore, SSRC recommends, in design practice, that the two aspects—stability of individual elements of the structure and stability of the structure as a whole—be considered independently. It is believed the full nonlinear programs illustrated above are reliable for the assessment of the maximum strength of frames in which stability is primarily a function of the formation of a number of plastic hinges, displacement effects, or a combination of the two. With respect to individual elements and small subassemblages, it has been found that the programs model elastic flexural instability accurately. Elastic torsional flexural instability of individual members in which St. Venant torsional resistance is the dominating torsional effect can also be well represented. Capability exists for including the effects of residual stress through the use of an axial stress dependent tangent modulus in the analysis of individual columns. The most pressing needs are for practical procedures for including the effects of warping restraint and initial imperfections, and for refined residual stress modeling. Research on these problems is underway and is expected to produce useful procedures for determining the maximum strength in most problems involving individual members and small subassemblies.
6. Drafting, detailing and fabrication control are additional important applications of interactive computer graphics. While they are essential functions in the production of satisfactory structures, the Cornell group does not plan to address them because they are not related closely enough to the structural engineering research we consider to be a necessary component of the projects undertaken.
7. The most serious limitation at present is in the area of transportability and software maintenance. Anyone who has entered the revolutionary field of computer-aided design will have encountered the problem. Both those who do research and development on such systems and those who plan their use are faced with a dilemma: either they can strive for a system that is robust and well-proven, or a system at the edge of the state-of-the-art. In the first case, they are apt to wind up with hardware and software that are muscle bound, slow and soon outdated. In the second case, they are apt to find themselves assuming responsibility for continual software development and conversion on a system configuration that is unique and constantly being upgraded. From the beginning, the project described here has been approached from the point of view of research dedicated to probing challenging areas of both academic and practical interest that profit-dependent organizations

cannot afford to study, are not prepared to study, or are not interested in studying because of their academic component. Publications, such as Refs. 7 through 11, and others in technical literature, demonstrate the quality of the research. On the applied side, we attempt to demonstrate, through papers such as this, some ideas that are ready for use in practical analysis and design by organizations prepared to assume the responsibility for implementation.

SUMMARY

An attempt has been made in this report to describe some of the ways in which advanced methods of analysis can be used to advantage in designing steel-framed structures. The key to utilization of methods presented is the medium of interactive computer graphics. Mainly through pictures, it has been shown how a framed structure may be described to the computer, analyzed either linearly or nonlinearly, and designed iteratively to meet either common conventional standards of acceptance or standards specially prescribed by the engineer.

Emphasis has been on the features of the work that should be of most direct application to the analysis and design of statically loaded frames at this time. A number of additional features relating to nonlinear behavior and earthquake resistant design have not been mentioned. Research directed toward the refinement of systems for both static and earthquake design continues, with emphasis on problems involving nonlinearity, three-dimensionality and dynamics.

A fear among practitioners is that computer-aided design can become "black box" design. Their concern is based on the feeling that analysis and design procedures will be so completely under the control of the computer that the user will have neither the understanding nor the control over the process essential to good engineering. Some fear such procedures will be used to produce automated designs in situations they were never intended to cover and that, in the absence of scrutiny by qualified professionals, results may be disastrous.

There is some justification for fear of misuse of analysis and design procedures. But it should not be a new one, nor should it be confined to advanced computer-aided design. The common computer programs which have been in use for a number of years can be grossly abused. There are also a number of conventional design tools that can be misapplied with equally alarming consequences. An example is the current interaction equation for combined compression and bending that has appeared in many specifications throughout the world for the past 30 years. If one does not have a thorough appreciation of the significance of the terms of this equation, one can insert in it inconsistent combinations of k, l_u, C_m, and C_b and "prove" things that are not so—or support use of member sizes that are not right. In common with all design aids, therefore, the interactive computer graphics procedures described here must be used with judgment.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under Grant No. PFR-7815357. The authors wish to thank John F. Abel and Donald P. Greenberg, co-principal investigators with the senior author, for invaluable contributions to the research. The analysis programs were developed by a number of graduate students, chiefly, John L. Gross, James G. Orbison and Marcelo Gattass. The vital contributions made by each are gratefully acknowledged.

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11. *Mutryn, T. A.* Inelastic, Nonlinear Building Connections *Master's thesis, Cornell University, Ithaca, N.Y., 1979.*