Automated Design of Space Trusses

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THE DESIGN by the elastic theory of a complex framed structure consists of the selection of an initial configuration followed by cyclic revisions. In each design cycle the structure is analyzed for predicted service loads and evaluated according to specified stress criteria. Then the structure is modified and the process repeated until a satisfactory design is obtained.

The task of computer programming for structural design involves certain considerations not encountered in analysis. Engineering decisions relating to geometry, load systems, types of members, support conditions, stress criteria, and methods of connection cannot be directly incorporated into a computer program. However, if these decisions are made beforehand and are reflected in the input data, an iterative procedure of analysis and revision can be programmed to produce convergence to a suitable design.

The role played by the computer in the design process may vary considerably. If the designer intervenes in each cycle, inspects the results, makes decisions, and alters parameters in accordance with his decisions, the operation is said to be "computer-aided design." On the other hand, if all parameters are predetermined and the computer is allowed to iterate to a final selection of member sizes without human intervention, the term "automated design" applies. This paper deals with the latter technique for the design of structures framed as space trusses.

The program described herein produces convergence to a design in which all members are either governed by allowable stress criteria of the 1963 AISC Specification[1] or are assigned a minimum acceptable size. An especially efficient method of analysis provides the base upon which the design program is constructed, but the program also includes important procedures for the estimation and selection of member sizes and the input and output of information. A small example problem and a large, complex roof truss designed in this manner are used to illustrate the capabilities of the program.

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EVOLUTION OF TECHNIQUES

The techniques described in this project evolved in several natural stages that deserve mention. The first stage consisted of repetitive applications of an existing computer program for the analysis of space trusses. This computer-aided technique allows the designer complete freedom in making revisions in each cycle but requires extensive hand calculations and many computer runs.

The second stage involved incorporating the analysis program into an estimation routine that cyclically revises cross-sectional areas of members on the basis of selected stress estimates. This semiautomatic type of program decreases the number of computer runs required but does not select particular member sizes.

In the third stage a subprogram was devised for selecting member sizes in accordance with the 1963 AISC Specification. Successive applications of this subprogram yield a final design.

The fourth stage consisted of combining the estimation and selection programs into a single program which calls upon one or both at the option of the designer. The combined program represents complete automation of the design process for selecting members of a space truss.

ANALYSIS

Method—The designer who possesses a fast and efficient program for analysis holds a key to the successful design of complex structures. The stiffness method of analysis, as applied to linearly-elastic framed structures,[2] proves to be very well suited for the purpose. In this approach the matrix equation expressing equilibrium conditions at nodal degrees of freedom takes the form:

$$\mathbf{SD} = \mathbf{A} \tag{1}$$

The identifier **A** in Equation (1) represents a column vector of joint loads, **D** denotes a vector of corresponding displacements, and **S** is a symmetric, positive definite matrix of stiffness influence coefficients for actions of type **A** due to unit displacements of type **D**. One method for determining the unknown displacements **D** consists of finding the inverse of **S** and then using it as a premultiplier on both sides of Equation (1) to produce:

$$\mathbf{D} = \mathbf{S}^{-1}\mathbf{A} \tag{2}$$

However, fewer arithmetic operations are required if the equations are solved simultaneously using the Cholesky method of decomposition.[3, 4] In this approach the symmetric stiffness matrix **S** is factored (or decomposed) into the product of a lower triangular matrix and an upper triangular matrix, each of which is the transpose of the other. Thus, the decomposition of **S** may be stated as:

$$\mathbf{S} = \mathbf{U}^T\mathbf{U} \tag{3}$$

The symbol **U** in Equation (3) denotes the upper triangular matrix, and $\mathbf{U}^T$ is its transpose. Elements of **U** are obtained from recurrence equations derived from Equation (3), after which the equilibrium equations can be solved in two steps. In preparation for the first step, substitute Equation (3) into Equation (1):

$$\mathbf{U}^T\mathbf{U}\mathbf{D} = \mathbf{A} \tag{4}$$

Then, define the vector **X** to be:

$$\mathbf{U}\mathbf{D} = \mathbf{X} \tag{5}$$

and rewrite Equation (4):

$$\mathbf{U}^T\mathbf{X} = \mathbf{A} \tag{6}$$

Since $\mathbf{U}^T$ is a lower triangular matrix, Equation (6) can be solved for the elements of **X** in a series of forward substitutions. The second step consists of solving for the elements of **D** in Equation (5) by a back-substitution procedure.

Band Matrices—Stiffness matrices for framed structures have bandwidths determined by the arrangement of the framing and the sequence of numbering joints. In most cases the joint numbering system can be selected to produce a small or moderate bandwidth. Computer storage requirements can be dramatically reduced by taking advantage of both the bandwidth and the inherent symmetry of the stiffness matrix. Furthermore, if the structure and its loads have one or more planes of symmetry, only a portion of the structure need be analyzed.

Figure 1 delineates the general form of the stiffness matrix for a typical framed structure. Only the upper portion of the band (including the diagonal elements) has to be generated and stored, as shown in the figure. The symbol *UBW* in Fig. 1 denotes the upper bandwidth, and *N* represents the size of the matrix. In a computer analysis it is convenient to store the upper band portion of the stiffness matrix in a rectangular array, as indicated in Fig. 2. With this arrangement the diagonal elements (shown shaded) appear in the first column of the array.

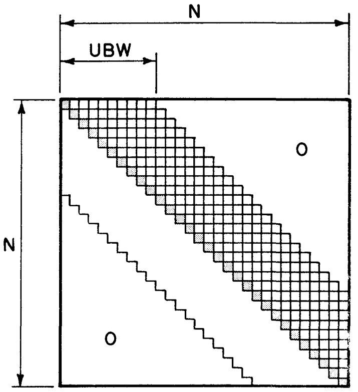


Fig. 1. Typical band stiffness matrix

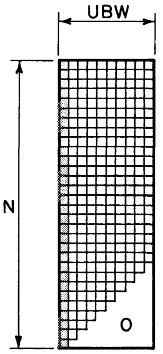


Fig. 2. Storage of upper band of stiffness matrix as a rectangular array

The decomposition and solution procedures described previously for a positive definite symmetric matrix apply equally well to a band-symmetric matrix. In this case the upper triangular matrix **U** is also a band matrix, and fewer calculations are required in the recurrence formulas due to the presence of zeros outside the band. Flow charts for procedures called DECOMPOSEBAND and SOLVEBAND, as well as general-purpose programs for analysis of framed structures, appear in the reference literature.[5]

Program for Analysis—Because of the cyclic nature of the design process, the program for analysis must be both rapid and effective in its use of computer storage. An essential feature of the decomposition method for banded matrices is the fact that all operations for a large structure can be performed completely in the core of the computer without resorting to the use of auxiliary storage units, such as magnetic disks or tapes. A broad outline for such a program follows, and this series of steps will be designated henceforth as the subprogram ANALYZE.

Subprogram ANALYZE:

1. Structure Stiffness Matrix
    a. Generation of upper band of stiffness matrix
    b. Decomposition of stiffness matrix (using Procedure DECOMPOSEBAND)
2. Construction of Matrices Associated with Loads
    a. Dead weights of members
        1. Fixed-end actions due to dead weights
        2. Conditions along lengths of members
    b. Equivalent joint loads
    c. Combined joint loads
3. Calculation of Results
    a. Joint displacements (using Procedure SOLVEBAND)
    b. Member actions
        1. End actions
        2. Maximum internal actions
    c. Support reactions

Table 1. Operators Used in Computer Programs

Operator	Symbol
Arithmetic Operators:	
Addition	+
Subtraction	−
Multiplication	x
Division	/
Exponentiation	*
Replacement Operator	←
Relational Operators:	
Less	<
Less or Equal	≤
Equal	=
Greater or Equal	≥
Greater	>
Not Equal	≠
Logical Operators:	
Both conditions true	AND
Either condition true	OR
Subsequent condition false	NOT

PROGRAM FOR DESIGN

Operators and Statements—In order to understand the flow charts included in this paper, the reader must be familiar with operators and statements used in computer programs. For convenient reference, symbols for commonly-used operators and statements are presented in Tables 1 and 2, respectively.

Table 2. Statements Used in Computer Programs

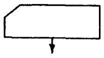
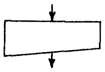
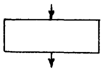
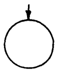
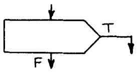
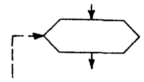
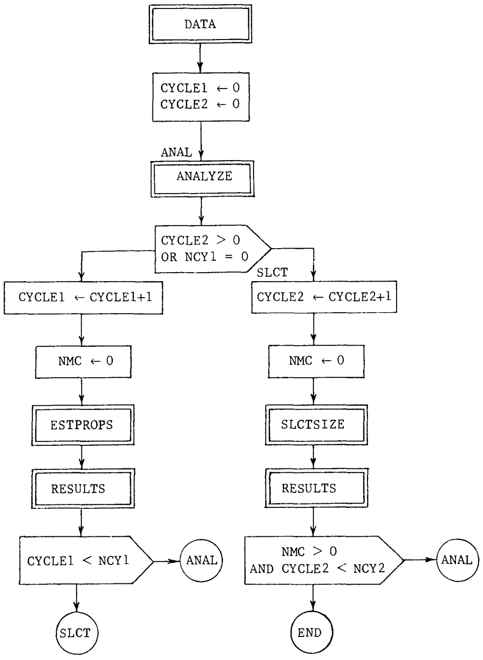
Type of Statement	Flow Chart Symbol
(a) Input	
(b) Output	
(c) Assignment	
(d) Unconditional Control	
(e) Conditional Control	
(f) Iterative Control	

Table 3. Flow Chart for Design Program



Main Program—Table 3 contains the flow chart for the main program in a form applicable to all types of framed structures. Although many of the identifiers in the chart are self-explanatory, a list of definitions for all symbols used in the paper is given in Appendix I. Double boxes in the flow chart represent subprograms (or procedures) that are utilized by the main program.

The first subprogram, called DATA, reads and prints information about the structure, the loads, and the design process. In each cycle of design the structure is analyzed for its working load conditions (including its own dead weight) using the procedure ANALYZE. The left-hand branch of the design program contains a procedure called ESTPROPS for estimating the properties of individual members. The number of passes through this branch is monitored by the control parameter CYCLE1 and is limited by the parameter NCY1. Procedure RESULTS, included in this branch, prints information from both ANALYZE and ESTPROPS.

A subprogram named SLCTSIZE for selecting member sizes appears in the right-hand branch of the design program. If the number of member changes NMC in a given cycle is greater than zero, a new cycle of analysis and selection is initiated. In addition, the number of passes through this branch is monitored and limited by the control parameters CYCLE2 and NCY2, respectively. Procedure RESULTS prints information from both ANALYZE AND SLCTSIZE.

General outlines of the procedures DATA and RESULTS follow. Flow charts for design procedures applicable to trusses only are given in the next section.

Procedure DATA:

1. Input and Print Structure Data
   a. Structure parameters
   b. Joint coordinates
   c. Member information; rotation matrix
   d. Joint restraint list; cumulative restraint list
2. Input and Print Load Data
   a. Load parameters
   b. Actions applied at joints
   c. Actions applied to members
      1. Types and intensities of loadings
      2. Fixed-end actions due to loads on members
      3. Conditions along lengths of members
3. Input and Print Design Data
   a. Design parameters
   b. Section properties

Procedure RESULTS:

1. Print Control Parameters (CYCLE1, CYCLE2, NMC) and Weight of Structure
2. Print Joint Displacements (optional)
3. Print Results for Members (optional)
   a. End actions
   b. Maximum internal actions
   c. Either of following:
      1. Results for cycle of estimation
      2. Results for cycle of selection
4. Print Support Reactions (optional)

Table 4. Preparation of Data for Space Truss Design

Data		Number of Cards	Items on Data Cards
Structure Data	a. Structure parameters	1	M NJ NR NRJ E
	b. Joint coordinates	NJ	J X[J] Y[J] Z[J]
	c. Member information (area optional)	M	I JJ[I] JK[I] (AX[I])
	d. Joint restraints	NRJ	J RL [3J-2] RL[3J-1] RL[3J]
Load Data	a. Load parameters	1	NLJ NLM UW
	b. Actions at joints	NLJ	J A[3J-2] A[3J-1] A[3J]
	c. Actions on members (vertical only)	NLM	I P[I] LDTYPE[I]
Design Data	a. Design parameters	1	MINSIZE MAXSIZE MINAREA CNB TNB COMP TENS FY K CON NCY1 NCY2
	b. Section properties	*	(Tabulated properties for available sizes)

*If section properties are read from data cards, the number of cards required is: MAXSIZE-MINSIZE+1

DESIGN PROCEDURES FOR TRUSSES

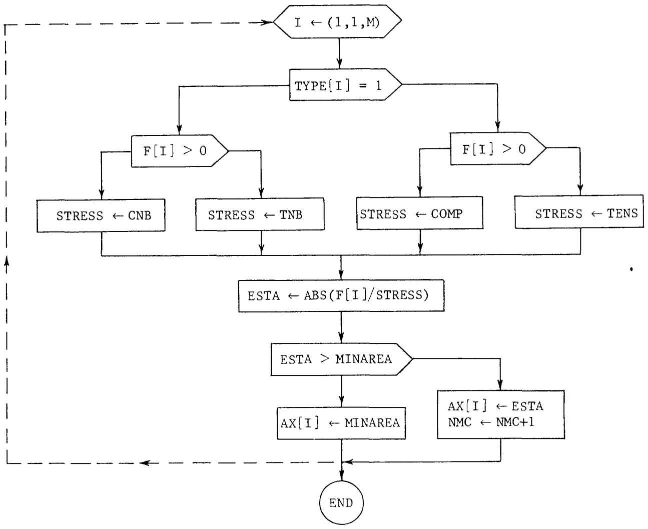
Preparation of Data—The manner in which a program is written depends to some extent upon the form in which the data is supplied. Therefore, the required input data for space truss design is given in Table 4. This table specifies the number of data cards required for each category of information as well as the items that are to be punched on the cards.

Estimation Procedure—The property of greatest interest for a truss member is its cross-sectional area. Therefore, the estimation procedure for a truss structure is named ESTAREA, and its flow chart is given in Table 5. In this procedure each member is examined individually, and its cross-sectional area is revised to conform to a set of selected criteria for axial stresses in members of different types. Two types of members are possible in a truss structure. Type 1 carries primarily axial stresses of tension or compression, and Type 2 resists a combination of axial and flexural stresses due to loads applied to the members. An orderly set of criteria for axial stressess (from the truss analysis alone) consists of four values chosen as follows:

Member Type 1:
- (a) Tension stress based upon an assumed percentage net area.
- (b) Compression stress based upon a desired value of KL/r.

Member Type 2:
- (a) Tension stress based upon an estimated percentage of the total combined stress.

Table 5. Flow Chart of Procedure ESTAREA for Trusses



(b) Compression stress based upon an estimated percentage of the total combined stress.

Thus, if each member in a truss is identified with respect to type, its cross-sectional area *AX[I]* can be recalculated in each cycle of estimation according to one of the above criteria (see Table 5). In any case the area *AX[I]* is not allowed to drop below a chosen minimum, MINAREA.

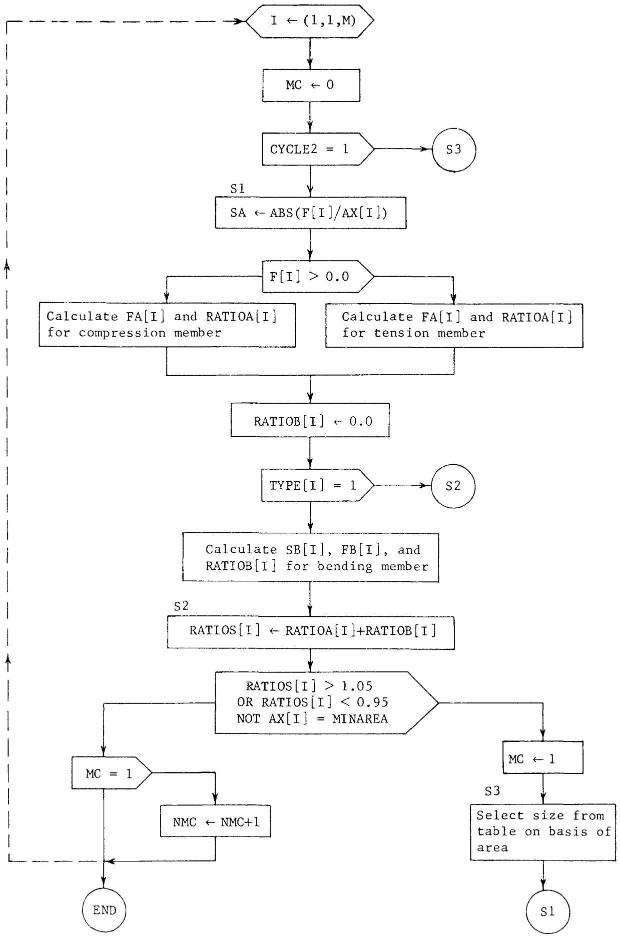
Selection Procedure—Table 6 shows a macroflow chart of the selection procedure SLCTSIZE for trusses. The makeup of this procedure implies that a table of standard sizes and their cross-sectional properties is available in the memory of the computer. Each member in the truss is checked to determine whether its working-stress condition satisfies the AISC interaction expressions within 5 percent. If not, a new member is selected and the process repeated until a satisfactory size is obtained. In addition, the area is not allowed to drop below a selected minimum.

The procedure for selection may accommodate one or more categories of standard shapes. Some commonly-used shapes for truss construction are wide-flange sections, square or circular tubes, double angles, and tees. A specialized procedure called SLCTWF, intended for the selection of wide-flange members only, is given in Appendix II.

EXAMPLES

Example 1—The braced platform in Fig. 3 carries the superimposed loads shown in addition to its own dead weight. This modest example is presented in order to

Table 6. Macro-Flow Chart of Procedure SLCTSIZE for Trusses



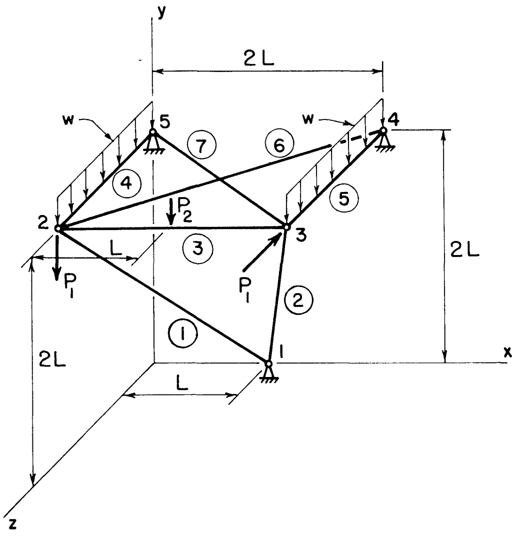


Fig. 3. Braced platform

illustrate the form of the input and output information for the truss design program. The platform is to be designed using ASTM A36 steel members with riveted or bolted connections, and numerical values of some of the parameters in the problem are as follows:

$$E = 29{,}000 \text{ ksi}; \quad L = 120 \text{ in.}; \quad K = 1.0$$
$$P_1 = 300 \text{ kips}; \quad P_2 = 25 \text{ kips}; \quad w = 0.25 \text{ kips/in.}$$

Input information and final results from the computer run of this example are included in Appendix III.

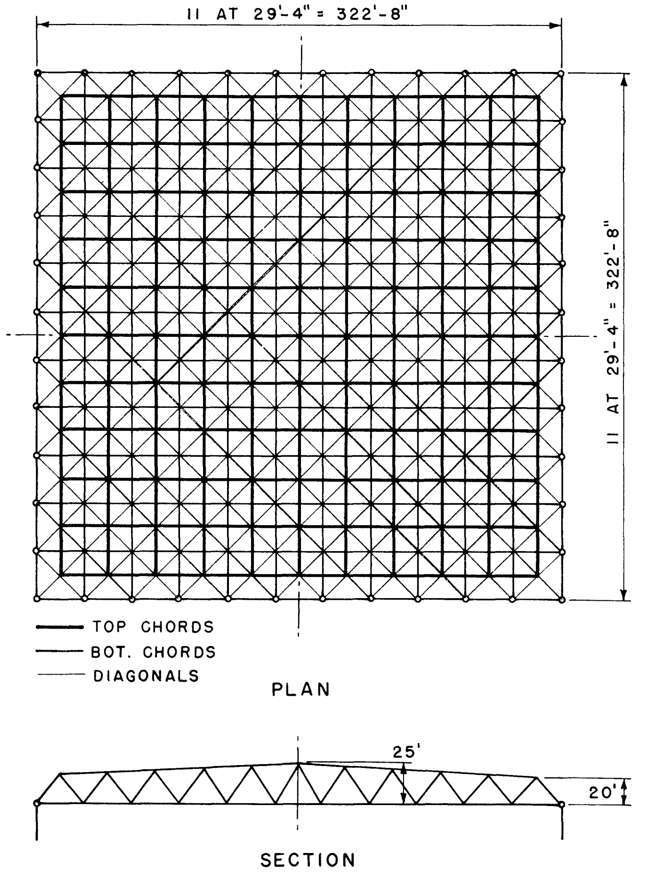


Fig. 4. Roof truss for University of South Carolina Memorial Hall

Example 2—Figure 4 shows a line drawing of a large roof truss for the University of South Carolina Memorial Hall (Field House), and Fig. 5 contains a perspective view drawn by a plotter linked to the computer. This structure was designed using wide-flange members of ASTM A36 steel with high-strength bolted connections. The truss spans 322 ft-8 in. in each direction, covering an area of approximately 104,000 sq ft. It is 20 ft deep at the edges and 25 ft deep at the center. A series of steel columns, spaced at 29 ft-4 in., supports the roof at its perimeter. Top chords and peripheral members carry loads applied along their lengths, but all other members resist only axial forces. The roof was required to carry 20 psf live loading in addition to the dead weight.

A 10WF33 was selected as the minimum acceptable member in the truss, and the following stress levels were adopted for the axial stress criteria used in the estimation procedure:

Member Type 1:
- (a) 20 ksi
- (b) −16 ksi

Member Type 2:
- (a) 12 ksi
- (b) −10 ksi

One-quarter of this doubly-symmetric structure was designed using a program coded in FORTRAN IV(H) for the IBM 360/67. The program utilizes the procedures ESTAREA and SLCTWF discussed above. In order to test the capabilities of this program, the example was run may times for various conditions; and some of the cases studied are as follows:

Case	*Initial Areas ($in.^2$)*	*K*	*Procedures Used*
1	10.0	—	ESTAREA only
2	100.0	—	ESTAREA only
3	10.0	1.0	SLCTWF only
4	100.0	1.0	SLCTWF only
5	10.0	1.0	ESTAREA and SLCTWF
6	100.0	0.75	ESTAREA and SLCTWF

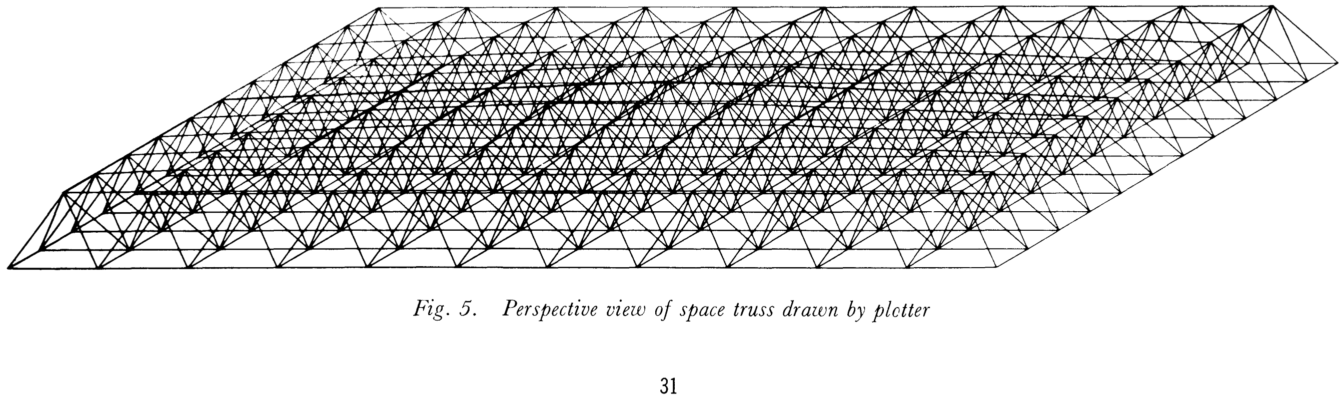


Fig. 5. Perspective view of space truss drawn by plotter

Figure 6 shows plots of the weight W for one-quarter of the truss resulting from Cases 1 and 2. The figure indicates that W_1 and W_2 converge to approximately the same value in about six passes through ESTAREA in spite of the fact that the initial areas differ by a factor of ten.

Results for Cases 3 and 4 are plotted in Fig. 7. The weights W_3 and W_4 converge to approximately the same value in about seven cycles of SLCTWF, but the number changes NMC_3 for Case 3 does not become zero until the sixteenth cycle. Most of the final member sizes selected in Case 4 were the same as those in Case 3. However, there were some members that differed slightly because of the combined effects of dissimilar initial areas and discontinuities in tabulated section properties.

Figure 8 summarizes the results of Cases 5 and 6, in which SLCTWF was used after ten cycles of ESTAREA (Cases 1 and 2). In these instances the number of member changes NMC_5 and NMC_6 become zero in seven and six cycles, respectively. Note that the weight W_6 converges to a value lower than W_5 because in Case 6 the effective length factor K was taken to be 0.75 instead of 1.0.

The average time required for one cycle of ESTAREA in this example was approximately 0.2 minutes, whereas that for one cycle of SLCTWF was about 0.3 minutes. In each of the cases studied a final design was obtained in less than 5 minutes. The design for Case 6 produced a weight W_6 of approximately 422 kips, or 16.2 psf. Deflection at the center of the truss due to its own dead weight was calculated to be approximately 2.5 in. Deflection under the total dead loading (estimated at 35 psf) was 5.5 in., and that due to live loading (20 psf) was found to be 2.9 in.

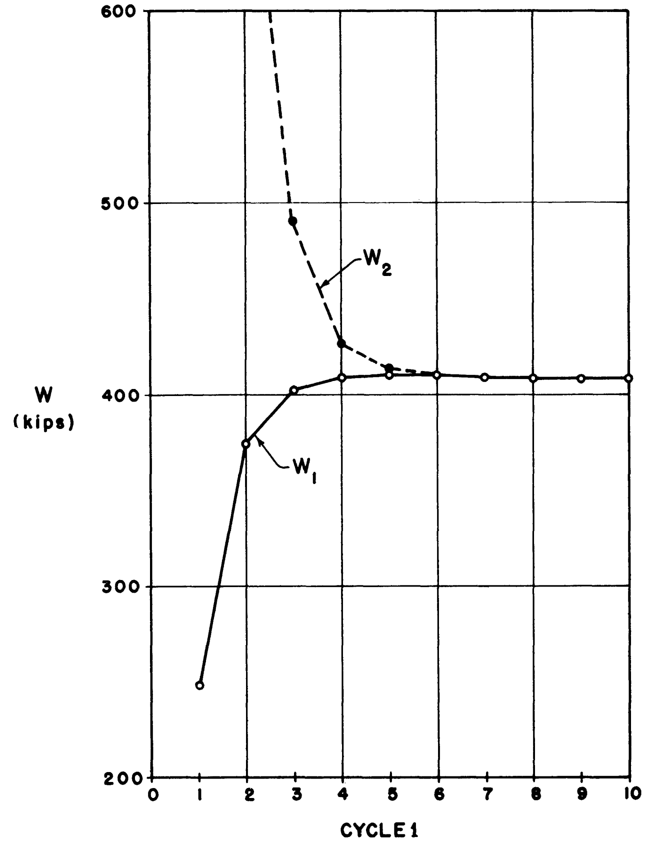


Fig. 6. Results of ESTAREA

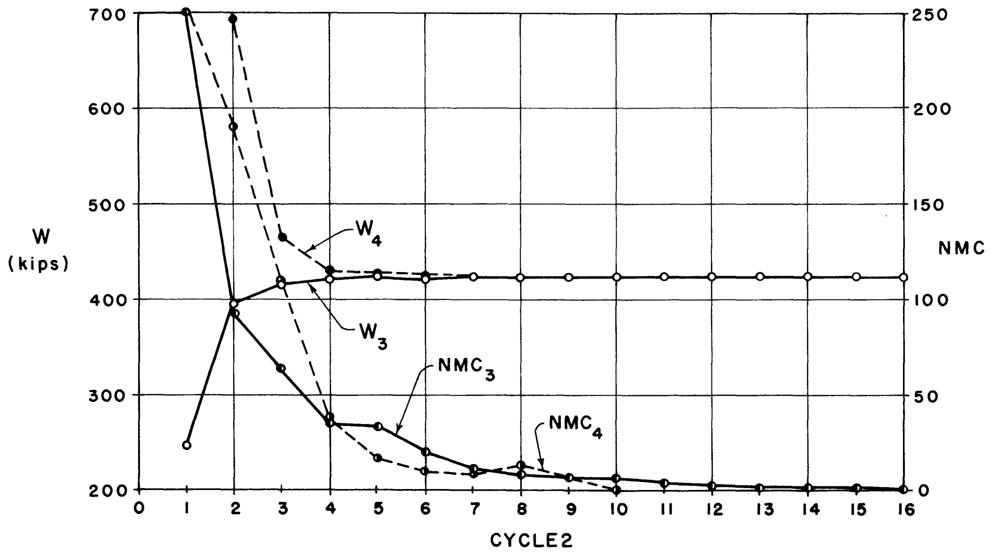


Fig. 7. Results using SLCTWF only

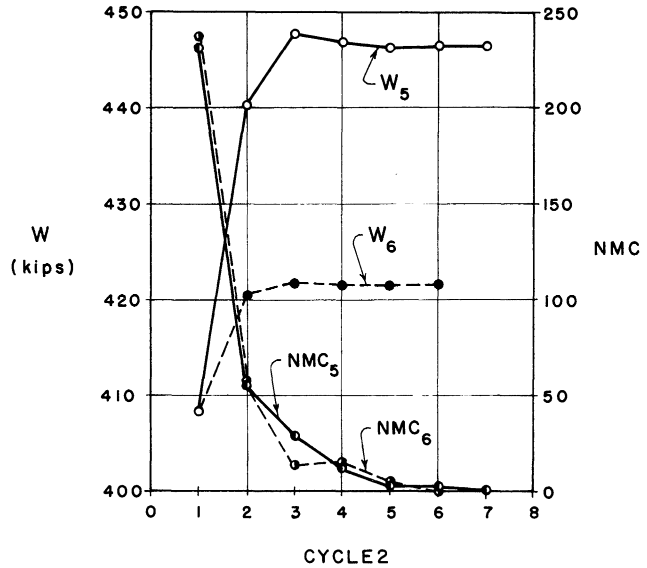


Fig. 8. Results using SLCTWF after ESTAREA

CONCLUSIONS

The techniques discussed in this paper represent a favorable combination of analytical power and practical design considerations. Because of the iterative nature of design, the method of analysis must be fast and efficient. Furthermore, the program must make effective use of the available storage in order to solve large problems within the core of the computer. The Cholesky method of decomposition, as applied to banded stiffness matrices, fulfills these these needs admirably.

The essential feature of the estimation procedure for a space truss consists of the assumption of four axial stress criteria and a cyclic revision of member areas to produce a preliminary design. On the other hand, the procedure for selection of member sizes systematically chooses standard steel sections in accordance with the 1963 AISC Specification and converges to the final design.

The roof truss for the University of South Carolina Field House serves as a suitable application for the design program. This large, complex space truss was designed by the program in less than 5 minutes without human intervention. Practically the same design was obtained for several cases in which various initial conditions and paths to the solution was chosen. Results from these studies indicate that approximately the same total number of design cycles is required whether Procedure SLCTWF is used itself or subsequent to the use of Procedure ESTAREA. However, the combined use of these routines is desirable because ESTAREA runs somewhat faster than SLCTWF.

Certain extensions of the truss design program appear to be feasible. Shapes other than wide-flange sections may be accommodated by replacing the procedure SLCTWF either with other special-purpose selection procedures or with a general-purpose procedure that selects from a variety of shapes. Multiple-load systems can be handled by converting certain vectors in the program to matrices and searching for the critical condition in each member. The program could also be extended to include the design of connections—at least to the point of choosing the type, number, and sizes of bolts, rivets, or welds.

A few other possibilities merit comment, although they are considered to be beyond the scope of this paper. The effects of varying the geometry of a space truss may be ascertained either by repeated runs of the design program or by incorporating it into a higher level program that varies the layout in some predetermined fashion. Design programs for frames with rigid joints may also be devised in a form similar to that for trusses. However, plastic design concepts compete with elastic theory for rigidly-connected frames, and two significantly different types of design programs may be of value in those cases. Future revisions of the AISC Specification will not nullify the basic truss design program because use of the specification provisions is restricted to the selection procedure only.

ACKNOWLEDGMENTS

Dr. Winfred O. Carter originally wrote some of the matrix procedures mentioned in this paper while he was a graduate student at Standford (1963). The structure used as an example was designed by the firm of Lyles, Bissett, Carlisle, and Wolff, Architects-Engineers, Columbia, S. C. The design techniques for the roof truss were conceived by the senior co-author while engaged as a consultant on the project. Details of the program were developed later in collaboration with the second co-author, who coded the program in FORTRAN.

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APPENDIX I

Nomenclature

Symbols Used in Text:

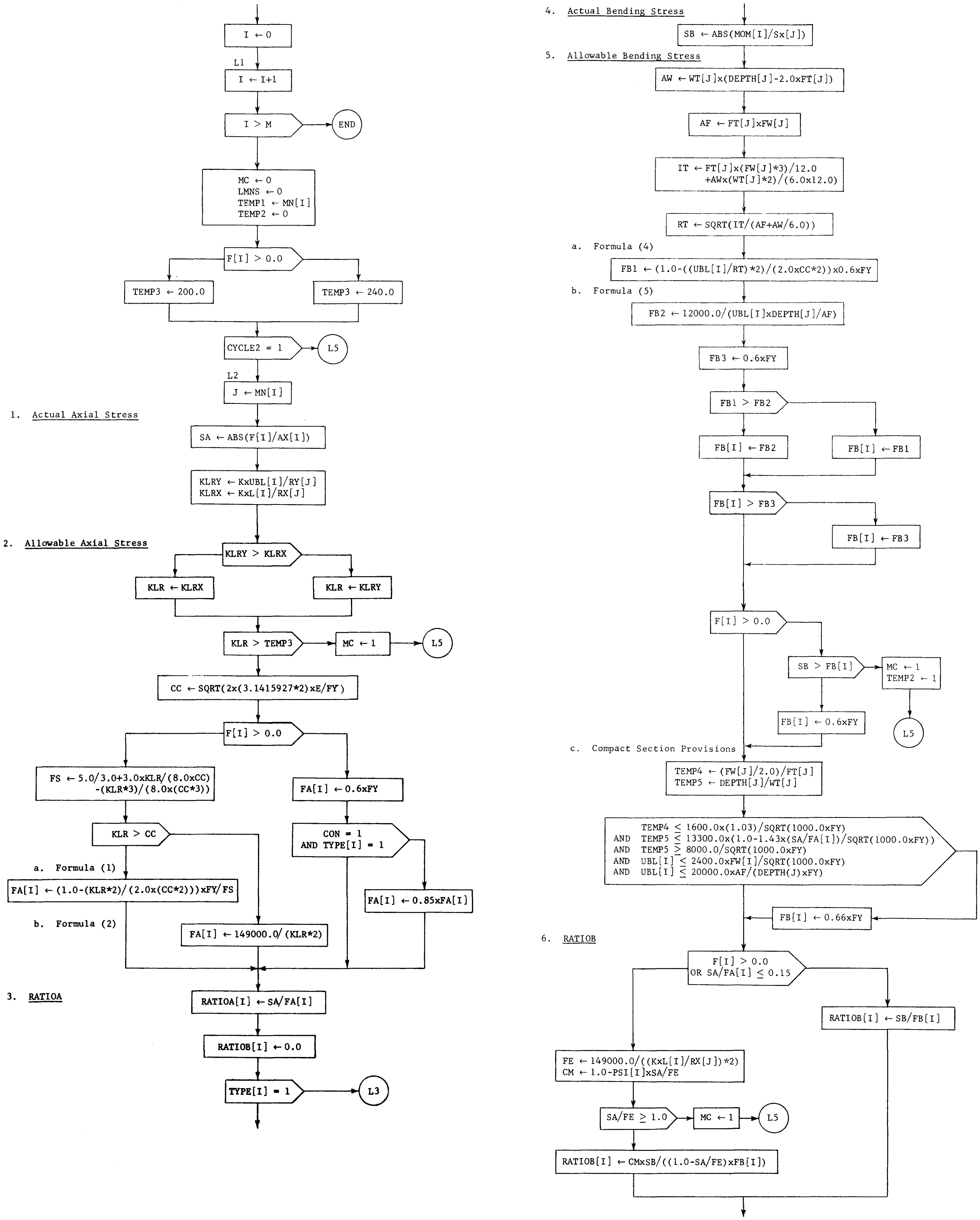
$\mathbf{A}$ = Action vector
$\mathbf{D}$ = Displacement vector
KL/r = Slenderness ratio
N = Number of rows in stiffness matrix
$\mathbf{S}$ = Stiffness matrix
$\mathbf{U}$ = Upper triangular matrix
UBW = Upper bandwidth of stiffness matrix
$\mathbf{X} = \mathbf{UD}$ (by definition)

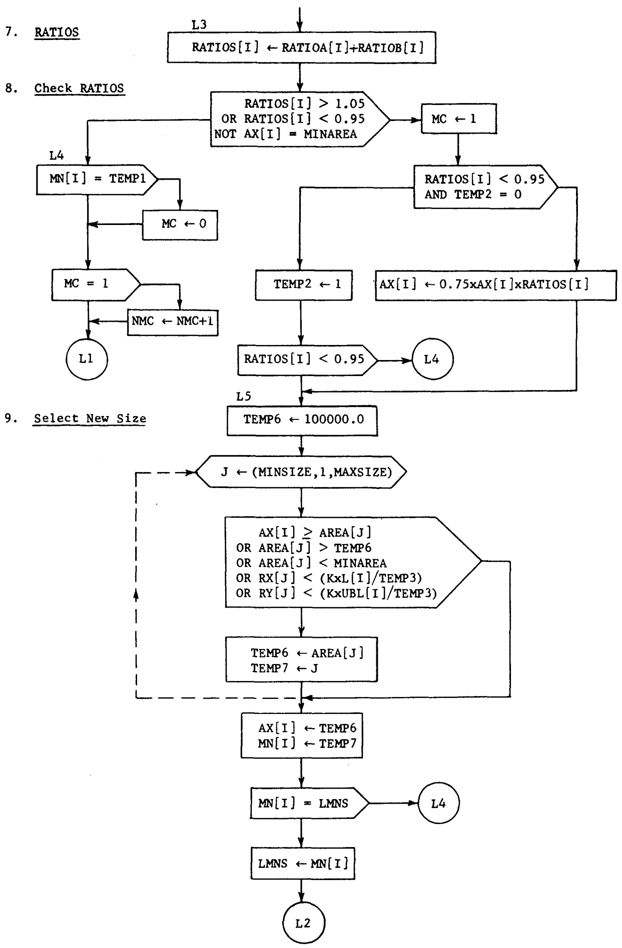
Symbols Used in Tables and Flow Charts:

A[ ] = Actions (loads) applied at joints
ABS = Absolute value function
AF = Area of flange
ANAL, *SLCT* = Labels
AREA[ ] = Cross-sectional area (from AISC tables)
AW = Area of web
AX[ ] = Cross-sectional area of member
CC = Column slenderness ratio delineating elastic from inelastic buckling
CM, *PSI*[ ] = Coefficients used in bending term of AISC interaction formula
CNB = Estimated compression stress for member of Type 2
COMP = Estimated compression stress for member of Type 1
CON = Type of connections
  0 Denotes welded
  1 Denotes bolted or riveted
*CYCLE*1 = Cycle for estimating member areas
*CYCLE*2 = Cycle for selecting member sizes
DEPTH[ ] = Member depth (from AISC tables)
E = Modulus of elasticity
ESTA = Estimated cross-sectional area
F[ ] = Axial force in member
FA[ ] = Allowable axial stress
FB[ ] = Allowable bending stress
*FB*1, *FB*2, *FB*3 = Temporary storage locations for allowable bending stress
FE = Euler buckling stress divided by factor of safety
FS = Factor of safety
FT[ ] = Flange thickness (from AISC tables)
FW[ ] = Flange width (from AISC tables)
FY = Yield stress
I, *J* = Subscripts (or indexes)
IT = Moment of inertia of tee-shaped section
JJ[ ] = Designation for *j* end of member (joint *j*)
JK[ ] = Designation for *k* end of member (joint *k*)
K = Effective length factor
KLR, *KLRX*, *KLRY* = *KL* over *R* ratio (*KL*/*R*)
L[ ] = Length of member
LDTYPE[ ] = Type of vertical load applied on member
  1 Denotes uniform on horizontal projection
  2 Denotes concentration at mid-point
  3 Denotes concentrations at third-points
  4 Denotes concentrations at quarter-points
LMNS = Last member number selected
M = Number of members
MAXSIZE = Index for maximum allowable size
MC = Member change
  0 Denotes no change
  1 Denotes change
MINAREA = Minimum allowable cross-sectional area
MINSIZE = Index for minimum allowable size
MN[ ] = Number of member selected
MOM[ ] = Internal moment
*NCY*1 = Number of cycles of estimation
*NCY*2 = Number of cycles of selection
NJ = Number of joints
NLJ = Number of loaded joints
NLM = Number of loaded members
NMC = Number of member changes in current cycle
NR = Number of support restraints
NRJ = Number of restrained joints
P[ ] = Actions (loads) applied to members
RATIOA[ ], *RATIOB*[ ] = Axial and bending portions of interaction formula
RATIOS[ ] = Sum of axial and bending portions of interaction formula
RL[ ] = Joint restraint list
  0 Denotes no restraint
  1 Denotes restraint
RT = Radius of gyration of tee-shaped section
RX[ ], *RY*[ ] = Radius of gyration with respect to the *x* and *y* axes (from AISC tables)
SA = Actual axial stress
SB = Actual bending stress
SIZE[ ] = Member name (from AISC tables)
SQRT = Square root function
STRESS = Stress
SX = Section modulus (from AISC tables)
*TEMP*1, *TEMP*2, etc. = Temporary storage locations
TENS = Estimated tension stress for Type 1 member
TNB = Estimated tension stress for Type 2 member
TYPE[ ] = Type of member
  1 Denotes axial force only
  2 Denotes axial and flexural
UBL[ ] = Unbraced length of member
UW = Unit weight of material
WT[ ] = Web thickness (from AISC tables)
X[ ], *Y*[ ], *Z*[ ] = *x*, *y*, and *z* coordinates of joint

APPENDIX II

Micro-Flow Chart of Procedure SLCTWF for Trusses





APPENDIX III

Computer Output for Example 1

```
AUTOMATED DESIGN OF SPACE TRUSSES

STRUCTURE PARAMETERS

       M      N     NJ     NR     NRJ        E

       7      6      5      9      3     29000.0

MEMBER INFORMATION

   MEMBER    JJ     JK      AX        L

     1        1      2     10.00    360.00

     2        1      3     10.00    360.00

     3        2      3     10.00    240.00

     4        2      5     10.00    240.00

     5        3      4     10.00    240.00

     6        2      4     10.00    339.41

     7        3      5     10.00    339.41

COORDINATES OF JOINTS AND JOINT RESTRAINTS

    JOINT      X          Y          Z          RL1     RL2     RL3

      1     120.00       0.0        0.0          1       1       1

      2       0.0      240.00     240.00         0       0       0

      3     240.00     240.00     240.00         0       0       0

      4     240.00     240.00       0.0          1       1       1

      5       0.0      240.00       0.0          1       1       1

LOAD CONDITION


  NLJ      NLM        UW
   2        3      0.000284
```

```
ACTIONS APPLIED AT JOINTS

    JOINT     A1         A2         A3

      2       0.0     -300.00       0.0

      3       0.0       0.0      -300.00

ACTIONS ON MEMBERS

MEMBER     LCTYPE      INTENSITY

   3          2         25.0000

   4          1          0.2500

   5          1          0.2500



ACTIONS AT ENDS OF RESTRAINED MEMBERS DUE TO LOADS

   MEMBER     AML1      AML2      AML3      AML4      AML5      AML6

      3       0.0      12.50      0.0       0.0      12.50      0.0

      4       0.0      30.00      0.0       0.0      30.00      0.0

      5       0.0      30.00      0.0       0.0      30.00      0.0

DESIGN PARAMETERS

 MINSIZ       MAXSIZ       MINAREA     CNB        TNB        COMP       TENS

10WF33       14WF426        9.71     10.000     12.000      8.000     18.000

  FY         K          CONNECTIONS         NCY1     NCY2

36.000      1.00     RIVETED OR BOLTED       10       10


CYCLE1= 10   CYCLE2=  3   NMC=  0

DEAD LOAD OF     12.482   IS INCLUDED IN THE ANALYSIS

JOINT DISPLACEMENTS

 JOINT       D1          D2          D3

   1    0.0          0.0          0.0

   2   -1.05519E-01-3.91814E-01 7.98407E-02

   3   -6.10820E-02 1.04940E-03-5.85933E-02

   4    0.0          0.0          0.0

   5    0.0          0.0          0.0


MEMBER END-ACTIONS

   MEMBER    AM 1      AM 2      AM 3      AM 4      AM 5      AM 6

      1     520.93     1.42      0.0     -518.39     1.42      0.0

      2      68.61     0.55      0.0      -67.63     0.55      0.0

      3     -96.33    13.11      0.0       96.33    13.11      0.0

      4    -269.55    30.95      0.0      269.55    30.95      0.0

      5     180.97    30.87      0.0     -180.97    30.87      0.0

      6    -108.74     0.47      0.0      108.74     0.47      0.0

      7     104.12     0.69      0.0     -104.12     0.69      0.0


MEMBER SELECTIONS

                    ACT.      ALLOW.               ACT.      ALLOW.
                    AXIAL     AXIAL                BEND.     BEND.
MEMBER   SIZE       STRESS    STRESS    RATIOA     STRESS    STRESS    RATIOB    RATIOS

   1    14WF127   -13.955    13.509     1.033                                   1.033

   2    10WF49     -4.765     7.417     0.642                                   0.642

   3    14WF61      5.369    21.600     0.249     16.667    21.600     0.772    1.020

   4    14WF95      9.647    21.600     0.447     12.332    21.600     0.571    1.018

   5    14WF87     -7.080    19.267     0.367     13.412    21.600     0.669    1.037

   6    10WF33     11.199    18.360     0.610                                   0.610

   7    10WF49     -7.230     8.345     0.866                                   0.866


SUPPORT REACTIONS

 JOINT      AR1          AR2          AR3

   1    -1.50514E 02 3.94497E 02 3.91852E 02

   4     7.68912E 01 3.13391E 01 1.04074E 02

   5     7.36222E 01 3.16462E 01-1.95926E 02



TIME OF THIS CYCLE WAS    0.026  MINUTES
```