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THESIS

DEVELOPMENT OF A COMPUTER PROGRAM FOR  
THE TESTING AND EVALUATION OF NUMERICAL  
OPTIMIZATION TECHNIQUES

by

James Edward Fitzgerald, III

June 1982

Thesis Advisor: G. N. Vanderplaats

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The finite element code may be used as a stand alone analysis tool or may be coupled to an optimizer of the user's choice. The finite element displacement method of analysis is used for static analysis and eigenvalues are calculated using the subspace iteration technique.

A major portion of this work is the software (user guide) which is presented in detail with examples and results. Explanation of how this code is coupled to an optimizer is given.

Design variables are member area sizes, joint coordinates, or both. Examples are presented to demonstrate the method.

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Development of a Computer Program for  
the Testing and Evaluation of Numerical  
Optimization Techniques

by

James Edward Fitzgerald III  
Lieutenant, United States Navy  
B.S., Middle Tennessee State University, 1975

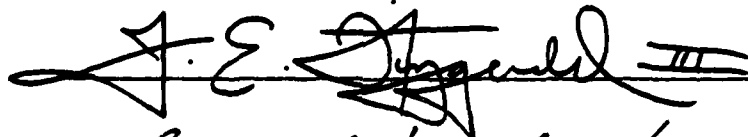
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## ABSTRACT

A three dimensional finite element code is written for truss analysis and design. Trusses may be designed for minimum weight subject to constraints on: member stresses, Euler buckling, joint displacements and system natural frequency. The optimum configuration may be found in addition to optimization with respect to member sizes.

The finite element code may be used as a stand alone analysis tool or may be coupled to an optimizer of the user's choice. The finite element displacement method of analysis is used for static analysis and eigenvalues are calculated using the subspace iteration technique.

A major portion of this work is the software (user guide) which is presented in detail with examples and results. Explanation of how this code is coupled to an optimizer is given.

Design variables are member area sizes, joint coordinates, or both. Examples are presented to demonstrate the method.

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## I. INTRODUCTION

Design optimization requires the minimization or maximization of some parameter. Optimization of structures has had continuing changes since its development in the early 1960's with an active area of research being elastic truss structures. The main goal is to design structural systems that efficiently perform specified purposes. For any design to be acceptable it must satisfy a variety of physical, aesthetic and economic constraints.

Since most physical problems can be modeled by some mathematical formulation a computer program can be written to perform the necessary calculations.

The purpose of this research was to develop a FINITE ELEMENT code that could be easily coupled to an optimizer, thus (1) allowing testing and comparison of various optimizers and (2) provide a useful design program in its own right.

The design problem considered in this study is the optimization of three-dimensional indeterminate trusses, for multiple static load conditions. The objective is to minimize the weight of the structure where the design variables are member sizes and joint coordinates. Constraints include stress, displacement, Euler buckling, and the natural frequency of the system.

This document describes the use and capabilities of the finite element computer code to be coupled to an optimizer. The user's manual presented in Chapter V contains a simple design example in which the program is coupled to the CONMIN optimization code [Ref. 1].

Additionally, guidelines for coupling the code to an optimizer of the user's choice are presented.

Several examples demonstrating the program under a variety of conditions are presented. Conclusions and recommendations for future work are given.

## II. OPTIMIZATION

### A. INTRODUCTION

The main goal of structural engineering optimization is to design structural systems that efficiently perform specified purposes. Selection of a specific algorithm must include the following considerations: 1) the structure should be analyzed as few times as possible, 2) the algorithm should minimize specific gradient information required, and 3) it should provide reasonable assurance that an optimum design will be reached.

The next few sections discuss the general formulation of the algorithm with respect to the above requirements.

### B. FORMULATION

Minimum weight design of trusses is presented in the general form of a mathematical programming problem as follows:

$$\text{Minimize } F(X) \quad (\text{Eq. 1})$$

Subject to:

$$g_j(x) \leq 0 \quad j=1,m \quad (\text{Eq. 2})$$

$$x_i^l \leq x_i \leq x_i^u \quad i=1,n \quad (\text{Eq. 3})$$

where  $F(X)$  is the objective function, in this case, weight of the structure be minimized.  $X$  is the vector of independent design variables and here contains the member cross-sectional areas as well as the coordinates of the joints. The inequality

constraints,  $g_j(x) \leq 0, j=1, m$ , must be satisfied for the design to be accepted as feasible. These include limits on stress, Euler buckling, joint displacements and the first fundamental frequency of the structure. Side constraints  $x_i^l$  and  $x_i^u$  are lower and upper bounds on the design variable. These may be treated as general inequality constraints.

### C. PARAMETERS

The design variables, constraints, and objective function considered in the design process are discussed here.

#### 1. Design Variables

The design variables the user has available are member cross-sectional area, reciprocal of member cross-sectional area, joint coordinates, or both member areas (or their reciprocals) and coordinates. The cross-sectional areas are  $A_k$ ,  $k=1, NE$ , where  $NE$  is the number of elements in the truss structure. The joint coordinates are  $X_{ij}$ ,  $i=1, 2, 3$   $j=1, NJ$ , where  $i$  is the coordinate axis,  $j$  is the joint number and  $NJ$  is the total number of joints. Design variable linking is allowed in both member sizing and coordinate design variables.

#### 2. Objective Function

The objective function considered here is weight.

$$\text{Weight (W)} = \sum_{i=1}^{NE} \rho_i A_i L_i \quad (\text{Eq. 4})$$

where  $\rho$  is the material density,  $A$  is the cross-sectional area and  $L_i$  is the length of the member. The truss may be made up of members of differing materials.

### 3. Constraints

$$\text{Stress: } \frac{\sigma_{ij}}{\bar{\sigma}^-} - 1 \leq 0 \quad \begin{array}{l} i=1, \text{NE} \\ j=1, \text{NLC} \end{array} \quad (\text{Eq. 5})$$

$$\frac{\sigma_{ij}}{\bar{\sigma}^+} - 1 \leq 0 \quad \begin{array}{l} i=1, \text{NE} \\ j=1, \text{NLC} \end{array} \quad (\text{Eq. 6})$$

where  $\sigma$  is the stress in member  $i$  under load condition  $j$ . NE is the number of elements and NLC is the number of loading conditions.

$\bar{\sigma}^-$  is the lower bound on the stress (maximum compressive stress) and  $\bar{\sigma}^+$  is the upper bound on the stress. The upper and lower bounds on stress may be different for each member, but are taken to be the same for every loading condition.

### 4. Euler Buckling

The stress at which Euler buckling occurs is given by:

$$\sigma_i E = \frac{-K_i A_i E_i}{L_i^2} \quad i=1, \text{NE} \quad (\text{Eq. 7})$$

where the subscript  $i$  corresponds to the member number,  $E_i$  is Young's modulus and  $K_i$  is a constant depending on the cross-sectional geometry of the member.

### 5. Displacement

Displacement limits are imposed at prescribed joints to create a constraint equation as follows:

$$\frac{u_{ijk}}{\bar{u}_{ijk}} - 1 \leq 0 \quad (\text{Eq. 8})$$

$$\frac{u_{ijk}}{\bar{u}_{ijk}^+} - 1 \leq 0 \quad (\text{Eq. 9})$$

where  $\bar{u}_{ijk}$  and  $\bar{u}_{ijk}^+$  are lower and upper bounds on the displacement at joint  $i$  in the coordinate direction  $j$  under loading condition  $k$ .

#### 6. Frequency

The first fundamental frequency of the structure is required to exceed the specified lower bound, so that

$$1 - \lambda/\bar{\lambda} < 0 \quad (\text{Eq. 10})$$

Reference 2 is an excellent source for the basic structural design formulation.

### III. FINITE ELEMENT METHOD

#### A. INTRODUCTION

Several features are desirable when the finite element methods of analysis are used in design optimization. First the number of analyses for the structure should be kept to a minimum. Second, the amount of gradient information required during the design process should be reduced to shorten run times and computer storage requirements. Third, the user should be able to specify only that gradient information desired.

#### B. ANALYSIS

Initial problem formulation includes member sizing, material properties (which may be different for each member), a set or sets of external loads, and specified support condition.

The analysis for the stresses and deflections must satisfy the conditions of equilibrium of forces at the nodes and compatibility of deformation. In this analysis the weight of the individual members are not part of the specified load conditions.

Additionally for this analysis the following assumptions are made. Trusses will be treated as discrete elements, and each element will be treated as pin-connected with loads and reactions supported at the joints.

The general method of solution is as follows. The Displacement (Stiffness) method reference 2 considers the joint displacement components as the unknowns, and written in matrix notation for the general case is

$$\underline{K}\underline{u} = \underline{P} \quad (\text{Eq. 1})$$

where  $\underline{K}$  is the global stiffness matrix,  $\underline{P}$  is the vector or vectors of applied loads, and  $\underline{u}$  is the vector of vectors of displacements.

Once displacements at every node are known, the internal forces and stresses are calculated by applying the appropriate force-deflection relationships.

When the system's natural frequency constraints are considered the design process requires the solution of an eigenproblem. This solution will determine the natural frequencies and normal modes of the structure. For linear elastic structures, the finite element approach leads to the following equation of motion with free vibration conditions,

$$\underline{M}\ddot{\underline{u}} + \underline{K}\underline{u} = 0 \quad (\text{Eq. 2})$$

where  $\underline{M}$  is the global mass matrix, and  $\ddot{\underline{u}}$  is the linear acceleration vector. This leads to an eigenvalue problem of the form  $(\underline{K} - \lambda \underline{M})\underline{u} = 0$ , and is solved here by the subspace iteration method reference 2.

### C. GRADIENTS OF CONSTRAINTS

Gradient computation of necessary functions in a design optimization process arise from the need for derivative information for efficient mathematical programming. For structural optimization the gradient of displacement with respect to the design variables,  $\partial u / \partial x$ , is needed from which  $\nabla G$ , is calculated for stress, displacement, and buckling.

Consider the finite element method  $\underline{\tilde{K}} \underline{u} = \underline{\tilde{P}}$ . Taking the derivative of both sides with respect to the design variable  $x_\ell$ , we have:

$$\frac{\partial}{\partial x_\ell} [\underline{\tilde{K}} \underline{u}] = \frac{\partial}{\partial x_\ell} (\underline{\tilde{P}}) \quad (\text{Eq. 3})$$

Assuming the loads  $P$  are not a function of  $x_\ell$ ,

$$\left[ \frac{\partial}{\partial x_\ell} (\underline{\tilde{K}}) \right] (\underline{u}) + \underline{\tilde{K}} \frac{\partial}{\partial x_\ell} (\underline{u}) = 0 \quad (\text{Eq. 4})$$

$$\text{Finally, we arrive at } \frac{\partial}{\partial x_\ell} (\underline{u}) = -\underline{\tilde{K}}^{-1} \left[ \frac{\partial}{\partial x_\ell} (\underline{\tilde{K}}) \right] \underline{u} \quad (\text{Eq. 5})$$

where  $\underline{\tilde{K}}^{-1}$  is the inverse of  $\underline{\tilde{K}}$ . For efficiency  $\underline{\tilde{K}}^{-1}$  is not actually calculated.

#### IV. PROGRAM FEATURES

##### A. INTRODUCTION

Each computer code has its own special features with which the user should be familiar if the program is to be used effectively. The next few sections will discuss an overview of the code and a typical problem that might be solved using the program. This problem along with other numerical examples will be presented in detail with results in Chapter VI.

The FINITE ELEMENT code was written to be used as a stand alone analysis program or an analysis code that could easily be coupled to an optimizer (of the user's choice) through simple modifications to the main driver program.

With user supplied area and coordinates coupled with input control parameters, the analysis mode will calculate the weight of the truss structure. Design variables may be chosen as member areas, joint coordinates, or both. Additionally, gradient information will be calculated with respect to area variables, coordinate variables or both. Coupled to an optimizer the code will optimize the weight of the structure and print the final optimization information and gradient vectors of specified constraints.

The following example of a 25-bar space tower presented in Tables (I-IV) shows some of the options the code contains.

Table I

## 25-BAR TOWER SAMPLE OUTPUT

## INPUT CONTROL PARAMETERS

INPUT PARAMETERS FOR STRUCTURAL ANALYSIS AND DESIGN ROUTINE, "SAD"  
25-BAR SPACE TRUSS (TEST CASE STRESS/DISP./BUCKLING/FREQ.)

## CONTROL PARAMETERS

NUMBER OF ELEMENTS, NE = 25  
TOTAL NUMBER OF JOINTS, NJ = 10  
JOINT CONSTRAINT VARIABLE, NCJ = 10  
NO. OF MATERIAL TYPES, NMT = 1  
NO. OF LOAD COND., NLC = 2  
NO. OF EIGENVALUES, NEIG = 2  
NO. OF EIGENVALUES CALC., NEIG1 = 2  
NO. OF FIXED MASSES, NFMAS = 2  
BUCKLING CONSTRAINT ID, NEUBC = 1  
NO. OF DISPL. CONST., NDSPLC = 4  
NO. OF FREQ. CONST., NFREQ = 1  
LUMPED MASS OPTION, LMASS = 0  
VARB. CALC. CONTROL, IDVCLC = 2

ACCELERATION DUE TO GRAVITY, GRAV = 0.38640E+03  
EIGENVALUE CONVERGENCE TOLORANCE, EPSEIG = 0.10000E-03

## JOINT COORDINATES

| JOINT | X            | Y            | Z           |
|-------|--------------|--------------|-------------|
| 1     | -0.37500E+02 | 0.0          | 0.20000E+03 |
| 2     | 0.37500E+02  | 0.0          | 0.20000E+03 |
| 3     | -0.37500E+02 | 0.37500E+02  | 0.10000E+03 |
| 4     | 0.37500E+02  | 0.37500E+02  | 0.10000E+03 |
| 5     | 0.37500E+02  | -0.37500E+02 | 0.10000E+03 |
| 6     | -0.37500E+02 | -0.37500E+02 | 0.10000E+03 |
| 7     | -0.10000E+03 | 0.10000E+03  | 0.0         |
| 8     | 0.10000E+03  | 0.10000E+03  | 0.0         |
| 9     | 0.10000E+06  | -0.10000E+03 | 0.0         |
| 10    | -0.10000E+03 | -0.10000E+03 | 0.0         |

## COORDINATE DESIGN VARIABLES

| JOINT | DESIGN VARIABLE |   |   | MULTIPLIER  |             |            |
|-------|-----------------|---|---|-------------|-------------|------------|
|       | X               | Y | Z | X           | Y           | Z          |
| 1     | 0               | 0 | 0 | 0.0         | 0.0         | 0.0        |
| 2     | 0               | 0 | 0 | 0.0         | 0.0         | 0.0        |
| 3     | 1               | 0 | 0 | -0.1000E+01 | 0.1000E+01  | 0.1000E+01 |
| 4     | 1               | 2 | 3 | 0.1000E+01  | 0.1000E+01  | 0.1000E+01 |
| 5     | 1               | 1 | 3 | 0.1000E+01  | -0.1000E+01 | 0.1000E+01 |
| 6     | 1               | 2 | 3 | -0.1000E+01 | -0.1000E+01 | 0.1000E+01 |
| 7     | 4               | 3 | 0 | -0.1000E+01 | 0.1000E+01  | 0.0        |
| 8     | 4               | 3 | 0 | 0.1000E+01  | 0.1000E+01  | 0.0        |
| 9     | 4               | 5 | 0 | 0.1000E+01  | -0.1000E+01 | 0.0        |
| 10    | 4               | 5 | 0 | -0.1000E+01 | -0.1000E+01 | 0.0        |

## MATERIAL PROPERTIES

| CODE | E          | RHO        | SIG-MIN     | SIG-MAX    | K-EULER    |
|------|------------|------------|-------------|------------|------------|
| 1    | 0.1000E+08 | 0.1000E+00 | -0.4000E+05 | 0.4000E+05 | 0.3927E+02 |

Table II

## 25-BAR TOWER SAMPLE OUTPUT

JOINT DISPLACEMENTS CALCULATED BY SYSTEM ROUTINE "SAD"

## LOAD CONDITION 1

| JOINT | DEGREE OF FREEDOM |              |              |
|-------|-------------------|--------------|--------------|
|       | 1                 | 2            | 3            |
| 1     | -0.21905E-02      | 0.38017E+00  | -0.27099E-01 |
| 2     | 0.21910E-02       | -0.38017E+00 | -0.27099E-01 |
| 3     | 0.90789E-01       | -0.15964E-01 | -0.68752E-01 |
| 4     | 0.91278E-01       | 0.17510E-01  | 0.36100E-01  |
| 5     | -0.90789E-01      | 0.15964E-01  | -0.68752E-01 |
| 6     | -0.91278E-01      | -0.17511E-01 | 0.36100E-01  |
| 7     | 0.0               | 0.0          | 0.0          |
| 8     | 0.0               | 0.0          | 0.0          |
| 9     | 0.0               | 0.0          | 0.0          |
| 10    | 0.0               | 0.0          | 0.0          |

## LOAD CONDITION 2

| JOINT | DEGREE OF FREEDOM |             |              |
|-------|-------------------|-------------|--------------|
|       | 1                 | 2           | 3            |
| 1     | 0.20126E-01       | 0.38860E+00 | -0.21023E-01 |
| 2     | 0.22911E-01       | 0.38860E+00 | -0.32687E-01 |
| 3     | 0.99531E-03       | 0.25951E-01 | -0.95653E-01 |
| 4     | 0.64733E-02       | 0.26707E-01 | -0.10297E+00 |
| 5     | 0.81493E-03       | 0.24435E-01 | 0.62874E-01  |
| 6     | 0.66536E-02       | 0.25142E-01 | 0.70194E-01  |
| 7     | 0.0               | 0.0         | 0.0          |
| 8     | 0.0               | 0.0         | 0.0          |
| 9     | 0.0               | 0.0         | 0.0          |
| 10    | 0.0               | 0.0         | 0.0          |

## JOINT COORDINATES

| JOINT | X Y Z        |              |             |
|-------|--------------|--------------|-------------|
|       | X            | Y            | Z           |
| 1     | -0.37500E+02 | 0.0          | 0.20000E+03 |
| 2     | 0.37500E+02  | 0.0          | 0.20000E+03 |
| 3     | -0.37500E+02 | 0.37500E+02  | 0.10000E+03 |
| 4     | 0.37500E+02  | 0.37500E+02  | 0.10000E+03 |
| 5     | 0.37500E+02  | -0.37500E+02 | 0.10000E+03 |
| 6     | -0.37500E+02 | -0.37500E+02 | 0.10000E+03 |
| 7     | -0.10000E+03 | 0.10000E+03  | 0.0         |
| 8     | 0.10000E+03  | 0.10000E+03  | 0.0         |
| 9     | 0.10000E+03  | -0.10000E+03 | 0.0         |
| 10    | -0.10000E+03 | -0.10000E+03 | 0.0         |

## JOINT COORDINATES

| JOINT | X Y Z        |              |             |
|-------|--------------|--------------|-------------|
|       | X            | Y            | Z           |
| 1     | -0.37500E+02 | 0.0          | 0.20000E+03 |
| 2     | 0.37500E+02  | 0.0          | 0.20000E+03 |
| 3     | -0.37500E+02 | 0.37500E+02  | 0.10000E+03 |
| 4     | 0.37500E+02  | 0.37500E+02  | 0.10000E+03 |
| 5     | 0.37500E+02  | -0.37500E+02 | 0.10000E+03 |
| 6     | -0.37500E+02 | -0.37500E+02 | 0.10000E+03 |
| 7     | -0.10000E+03 | 0.10000E+03  | 0.0         |
| 8     | 0.10000E+03  | 0.10000E+03  | 0.0         |
| 9     | 0.10000E+03  | -0.10000E+03 | 0.0         |
| 10    | -0.10000E+03 | -0.10000E+03 | 0.0         |

Table III

25-BAR TOWER SAMPLE OUTPUT

AREA/COORDINATE VARIABLES

THERE ARE 8 AREA DESIGN VARIABLES

INITIAL VALUES  
0.20000E+01 0.20000E+01 0.20000E+01 0.20000E+01 0.20000E+01 0.20000E+01

LOWER BOUNDS  
0.10000E-04 0.10000E-04 0.10000E-04 0.10000E-04 0.10000E-04 0.10000E-04

UPPER BOUNDS  
0.50000E+02 0.50000E+02 0.50000E+02 0.50000E+02 0.50000E+02 0.50000E+02

THERE ARE 5 COORDINATE VARIABLES

INITIAL VALUES  
0.37500E+02 0.37500E+02 0.10000E+03 0.10000E+03 0.10000E+03

LOWER BOUNDS  
0.10000E+00 0.10000E+00 0.10000E+00 0.10000E+00 0.10000E+00

UPPER BOUNDS  
0.50000E+03 0.50000E+03 0.50000E+03 0.50000E+03 0.50000E+03

JOINT DISPLACEMENT CONSTRAINTS

DIRECTION 1=X, 2=Y, 3=Z, 0=RESULTANT

| NODE | DIR. | LOAD COND. | LOWER BOUND | UPPER BOUND |
|------|------|------------|-------------|-------------|
| 1    | 1    | 1          | -0.3500E+00 | 0.3500E+00  |
| 2    | 1    | 1          | -0.3500E+00 | 0.3500E+00  |
| 1    | 2    | 1          | -0.3500E+00 | 0.3500E+00  |
| 2    | 2    | 1          | -0.3500E+00 | 0.3500E+00  |

FREQUENCY CONSTRAINTS  
LOWER BOUNDS IN CPS

| FREQUENCY NUMBER | LOWER BOUND |
|------------------|-------------|
| 1                | 0.1600E+02  |

Table IV  
25-BAR TOWER SAMPLE OUTPUT

FINAL OPTIMIZATION INFORMATION

FINAL OPTIMIZATION INFORMATION

OBJ = 0.267256E+03

DECISION VARIABLES (X-VECTOR)

|     |             |             |             |             |             |             |
|-----|-------------|-------------|-------------|-------------|-------------|-------------|
| 1)  | 0.14595E+01 | 0.74285E+00 | 0.98392E+00 | 0.10425E+01 | 0.11271E+01 | 0.73567E+00 |
| 7)  | 0.85953E+00 | 0.69571E+00 | 0.39367E+02 | 0.46934E+02 | 0.13895E+03 | 0.73636E+02 |
| 13) | 0.68280E+02 |             |             |             |             |             |

CONSTRAINT VALUES (G-VECTOR)

|      |              |              |              |              |              |              |
|------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1)   | -0.29866E-01 | -0.99317E+00 | -0.10068E+01 | -0.10068E+01 | -0.99316E+00 | -0.19707E+01 |
| 7)   | -0.29252E-01 | -0.29252E-01 | -0.19707E+01 | -0.10160E+01 | -0.98405E+00 | -0.10063E+01 |
| 13)  | -0.10090E+01 | -0.99103E+00 | -0.10035E+01 | -0.71485E+00 | -0.12854E+01 | -0.53664E+00 |
| 19)  | -0.89607E+00 | -0.11039E+01 | -0.63131E+00 | -0.12343E+01 | -0.76507E+00 | -0.13813E+01 |
| 25)  | -2.91932E+00 | -0.10807E+01 | -0.86905E+00 | -0.12349E+01 | -0.76507E+00 | -0.13813E+01 |
| 31)  | -0.10255E+01 | -0.97413E+00 | -0.10420E+01 | -0.71485E+00 | -0.12343E+01 | -0.53664E+00 |
| 37)  | -0.10491E+01 | -0.95088E+00 | -0.10797E+01 | -0.12113E+01 | -0.78870E+00 | -0.11298E+01 |
| 43)  | -0.75447E+00 | -0.12455E+01 | -0.84920E+00 | -0.65536E+00 | -0.13446E+01 | -0.78832E+00 |
| 49)  | -0.11021E+01 | -0.89789E+00 | -0.10627E+01 | -0.65536E+00 | -0.13446E+01 | -0.78832E+00 |
| 55)  | -0.76670E+00 | -0.12331E+01 | -0.85683E+00 | -0.12113E+01 | -0.78870E+00 | -0.11298E+01 |
| 61)  | -0.11145E+01 | -0.88546E+00 | -0.10703E+01 | -0.10478E+01 | -0.95216E+00 | -0.10412E+01 |
| 67)  | -0.10366E+01 | -0.96343E+00 | -0.10315E+01 | -0.10478E+01 | -0.95216E+00 | -0.10412E+01 |
| 73)  | -0.10589E+01 | -0.94111E+00 | -0.10507E+01 | -0.10170E+01 | -0.98304E+00 | -0.10095E+01 |
| 79)  | -0.11018E+01 | -0.89817E+00 | -0.10570E+01 | -0.10170E+01 | -0.98304E+00 | -0.10095E+01 |
| 85)  | -0.92366E+00 | -0.10764E+01 | -0.95723E+00 | -0.11010E+01 | -0.89902E+00 | -0.14719E+01 |
| 91)  | -0.11726E+01 | -0.42740E+00 | -0.18066E+01 | -0.85724E+00 | -0.11428E+01 | -0.33284E+00 |
| 97)  | -0.80677E+00 | -0.11932E+01 | -0.96984E-01 | -0.85724E+00 | -0.11428E+01 | -0.33284E+00 |
| 103) | -0.11518E+01 | -0.34815E+00 | -0.17090E+01 | -0.11010E+01 | -0.89902E+00 | -0.14719E+01 |
| 109) | -0.78603E+00 | -0.12140E+01 | -0.17345E-04 | -0.11951E+01 | -0.80493E+00 | -0.17520E+01 |
| 115) | -0.84000E+00 | -0.11600E+01 | -0.36325E+00 | -0.74877E+00 | -0.12512E+01 | -0.31550E+01 |
| 121) | -0.81120E+00 | -0.11888E+01 | -0.27219E+00 | -0.74877E+00 | -0.12512E+01 | -0.31550E+01 |
| 127) | -0.11316E+01 | -0.86840E+00 | -0.15073E+01 | -0.11951E+01 | -0.80493E+00 | -0.17520E+01 |
| 133) | -0.11028E+01 | -0.89721E+00 | -0.13962E+01 | -0.99416E+00 | -0.10058E+01 | -0.98209E+00 |
| 139) | -0.12234E+01 | -0.77661E+00 | -0.16847E+01 | -0.90920E+00 | -0.10908E+01 | -0.72168E+00 |
| 145) | -0.72096E+00 | -0.12790E+01 | -0.14473E+00 | -0.99416E+00 | -0.10058E+01 | -0.98209E+00 |
| 151) | -0.68057E+00 | -0.13143E+01 | -0.21237E-01 | -0.90919E+00 | -0.10908E+01 | -0.72158E+00 |
| 157) | -0.11831E+01 | -0.81690E+00 | -0.15612E+01 |              |              |              |

THERE ARE 7 ACTIVE CONSTRAINTS

CONSTRAINT NUMBERS ARE  
1 7 8 111 120 126 153

THERE ARE 0 VIOLATED CONSTRAINTS

THERE ARE 0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERION  
ITFR EQUALS ITMAX

NUMBER OF ITERATIONS = 20

|                                          |    |       |
|------------------------------------------|----|-------|
| OBJECTIVE FUNCTION WAS EVALUATED         | 60 | TIMES |
| CONSTRAINT FUNCTIONS WERE EVALUATED      | 60 | TIMES |
| GRADIENT OF OBJECTIVE WAS CALCULATED     | 20 | TIMES |
| GRADIENTS OF CONSTRAINTS WERE CALCULATED | 20 | TIMES |

## V. USER GUIDE

### A. INTRODUCTION

In developing any computer code for engineering analysis, it is necessary to additionally develop concise, easily understood software. This USER GUIDE is written to be easily followed assuming minimal FORTRAN knowledge. The format follows that of the optimization code, COPES/CONMIN, reference 1.

This chapter is devoted to acquainting the user with the code and necessary input data. A simple 3-bar truss analysis is used as the example.

### B. GENERAL FORMULATION

Each data card is set up to show the input data necessary with the 3-bar truss example underneath. Formats are of "I5" and "F10.0" type. "I" formats must be right justified, and "F" formats must have the decimal point. The number of cards read per data block is listed at the bottom of each block.

### C. CONSTRAINTS

Constraints are calculated and stored in the G vector as listed in the following chart. The total number of constraints  $NCON = 2*NDSPLC + NFREQ + NE*NLC$ . When any of the constraints are missing from the G vector, all constraints are moved up.

For example, if there is no frequency constraint, then a displacement constraint would fill the first location of the G vector.

$$G = \left\{ \begin{array}{ll} \begin{array}{l} \frac{\lambda_1}{\bar{\lambda}_1} - 1 \\ \vdots \\ \frac{\lambda_i}{\bar{\lambda}_i} - 1 \\ \vdots \\ \frac{u_1}{\bar{u}_1} - 1 \\ \vdots \\ \frac{u_n}{\bar{u}_n} - 1 \end{array} & \begin{array}{l} \text{NFREQ} \\ \text{(FREQUENCY CONSTRAINTS)} \\ \text{-----} \\ 2 * \text{NDSPLC} * \text{NLC} \\ \text{(DISPLACEMENT CONSTRAINTS)} \\ \text{-----} \end{array} \\ \begin{array}{l} \frac{\sigma_{11}}{\bar{\sigma}_1} - 1 \\ \vdots \\ \frac{\sigma_{11}}{\bar{\sigma}_1 E} - 1 \\ \text{-----} \\ \frac{\sigma_{21}}{\bar{\sigma}_2} - 1 \\ \vdots \\ \frac{\sigma_{NE}}{\bar{\sigma}_{NE} E} - 1 \end{array} & \begin{array}{ll} \begin{array}{l} \text{MEMBER \#1} \\ \text{LC \#1} \end{array} & \begin{array}{l} \text{STRESS AND} \\ \text{BUCKLING} \end{array} \\ \text{-----} \\ \begin{array}{l} \text{MEMBER \#2} \\ \text{LC \#1} \end{array} & \begin{array}{l} \text{STRESS AND} \\ \text{BUCKLING} \end{array} \\ \text{-----} \\ \begin{array}{l} \text{MEMBER \#NE} \\ \text{LC \#NLC} \end{array} & \begin{array}{l} \text{STRESS AND} \\ \text{BUCKLING} \end{array} \end{array} \right.$$

#### D. EXAMPLE

The initial layout of the 3-bar truss is shown in Figure 6.1. Stress constraints were imposed as well as constraints on Euler buckling, displacement, and first fundamental frequency.

With geometry specified as per the figure, 2 independent load conditions ( $P_1, P_2$ ) were imposed with 3 member sizing variables ( $A_1, A_2, A_3$ ) linked so that  $A_1=X(1)$ ,  $A_2=X(2)$ ,  $A_3=X(1)$ .

##### 1. Properties/Conditions

The material used had a density ( $\rho$ )=0.1 lb/in<sup>3</sup>. Young's Modulus was selected as  $10^7$  psi.

LOADS:  $P_1=P_2= 20,000$  lbs.

STRESS LIMITS:  $-15,000 < \sigma_i < 20,000$  psi  $i=1,3$

Symmetry was maintained by linking of variables so  $A_1=A_3$ . Initial design began with  $A_1=A_2=A_3= 1.0$  in. One non-structural mass of 500 lbs was attached at joint 2. Displacement constraints were imposed between  $-.02$  and  $.02$  inches in the x-direction with the first natural frequency limited to a value  $\omega_n < 20$  Hz.

##### 2. Input Control Parameters

The following input control parameters are given for ease of the following example.  $NE=3$ ,  $NJ=4$ ,  $NCJ=4$ ,  $NMT=1$ ,  $NLC=2$ ,  $NEIG=2$ ,  $NEIG1=2$ ,  $NFMAS=1$ ,  $NEUBC=1$ ,  $NDSPLC=2$ ,  $NFREQ=1$ ,  $LMAS=0$ ,  $IDVCLC=2$ . Table V is a listing of commonly used nomenclature.

# TABLE V

## COMMON VARIABLE NOMENCLATURE

A- MEMBER'S CROSS-SECTIONAL AREA  
 BL- LOWER BOUND ON DISPLACEMENTS  
 BU- UPPER BOUND ON DISPLACEMENTS  
 DIR- DIRECTION 1=X, 2=Y, 3=Z  
       0=LIMIT ON RESULTANT DISPL.  
 E- YOUNG'S MODULUS  
 ELNO- ELEMENT NUMBER  
 EPSEIG- CONVERGENCE TOLERANCE OF EIGENVALUE  
       SOLUTIONS (DEFAULT=.0001)  
 PC1,PC2,.....PCN- LOWER BOUND ON FIRST, SECOND, ETC.  
       SYSTEM NATURAL FREQUENCY  
 FX- LOAD FORCES BEING APPLIED IN THE X DIRECTION  
 FY- LOAD FORCES BEING APPLIED IN THE Y DIRECTION  
 FZ- LOAD FORCES BEING APPLIED IN THE Z DIRECTION  
 GRAV- ACCELERATION DUE TO GRAVITY (DEFAULT= 386.4)  
 IX- CONSTRAINT IDENTIFIER. IF NON-ZERO THE X-DOF  
       IS CONSTRAINED  
 IY- CONSTRAINT IDENTIFIER. IF NON-ZERO THE Y-DOF  
       IS CONSTRAINED  
 IZ- CONSTRAINT IDENTIFIER. IF NON-ZERO THE Z-DOF  
       IS CONSTRAINED  
 JN- JOINT NUMBER (GLOBAL)  
 KEULER- EULER BUCKLING COEFFICIENT FOR BAR  
       ELEMENTS  
 LC- LOAD CONDITION  
 LMASS- LUMPED MASS OPTIONS. IF LMASS .NE. 0 LUMPED  
       MASS MATRIX USED  
       IF LMASS =0 CONSISTENT MASS MATRIX USED  
 NEIG1- NUMBER OF EIGENVALUE/EIGENVECTOR TO BE  
       EVALUATED DEFAULT =MIN(2\*NEIG, NEIG+8)  
 NEUBC- BUCKLING CONSTRAINT IDENTIFIERS. IF NEUBC.  
       NE.0 EULER BUCKLING WILL BE IMPOSED IN  
       BAR ELEMENTS  
 NPMAS- NUMBER OF FIXED MASSES ATTACHED TO THE  
       STRUCTURE  
 NFREQ- NUMBER OF FREQUENCY CONSTRAINTS  
 NID- NUMBER OF INDEPENDENT DEGREES OF FREEDOM  
 NJ- NUMBER OF JOINTS  
 NLC- NUMBER OF LOADING CONDITIONS  
 NLJ- NUMBER OF LOADED JOINTS FOR THIS LOAD CONDITION  
 NMT- NUMBER OF SEPARATE MATERIAL TYPES  
 RHO- MATERIAL DENSITY  
 SIGMIN- MINIMUM ALLOWABLE STRESS  
 SIGMAX- MAXIMUM ALLOWABLE STRESS  
 XA- INITIAL VALUE OF AREA DESIGN VARIABLE  
 XAL- LOWER BOUND  
 XAU- UPPER BOUND  
 XC- INITIAL VALUE OF COORDINATE DESIGN VARIABLE  
 XCL- LOWER BOUNDS  
 XCU- UPPER BOUNDS

The following user's manual is divided into blocks A through M. Appearing directly below each data field line are the parameters for the 3-bar truss example. It is important to note the user may choose any units; however, all units must remain consistent throughout the problem.

DATA BLOCK A

DESCRIPTION: Title Card

Format and Example

| TITLE | FORMAT |
|-------|--------|
|       | 20A4   |

|                       |
|-----------------------|
| 3-BAR TRUSS (EXAMPLE) |
|-----------------------|

FIELD

CONTENTS

1

ANY 80 CHARACTER TITLE  
MAY BE GIVEN ON THIS LINE

**DATA BLOCK B**

**DESCRIPTION:** Control Parameters

**Format and Example**

|    |    |     |     |     |       |        |      |        |
|----|----|-----|-----|-----|-------|--------|------|--------|
| NE | NJ | NCJ | NMT | NLC | NEUBC | NDSPLC | NPRI | FORMAT |
|    |    |     |     |     |       |        |      | 8I5    |

|   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| 3 | 4 | 4 | 1 | 2 | 1 | 2 | 0 |
|---|---|---|---|---|---|---|---|

|      |       |        |       |        |       |        |
|------|-------|--------|-------|--------|-------|--------|
| NEIG | NEIG1 | NPHASS | NFREQ | IDVCLC | IRECP | FORMAT |
| 2    | 2     | 1      | 1     | 2      | 0     | 5I5    |

|  |  |  |  |  |  |
|--|--|--|--|--|--|
|  |  |  |  |  |  |
|--|--|--|--|--|--|

**NOTE: DEFINITIONS OF INPUT CONTROL PARAMETERS FOR  
PROGRAM NEXT PAGE.**

| <u>FIELD</u> | <u>CONTENT</u>                                                                                                                                   |
|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| 1            | NE-number of elements                                                                                                                            |
| 2            | NJ-number of joints                                                                                                                              |
| 3            | NCJ-number of constrained joints                                                                                                                 |
| 4            | NMT-number of separate material types                                                                                                            |
| 5            | NLC-number of load conditions                                                                                                                    |
| 6            | NEUBC-buckling constraint identifier<br>(If NEUBC.NE.0 -EULER buckling constraints will be imposed on bar ele.)                                  |
| 7            | NDSPLC-number of displacement constraints                                                                                                        |
| 8            | NPR1-input print control (if NPR1.ne.0<br>input information will not be printed)                                                                 |
| 1            | NEIG-number of precise eigenvalues to<br>be evaluated                                                                                            |
| 2            | NEIG1-number of eigenvalues to be evaluated<br>DEFAULT=min. of (2*NEIG , NNEIG+8)                                                                |
| 3            | NPMASS-number of fixed masses attached to<br>structure                                                                                           |
| 4            | NPFREQ-number of frequency constraints                                                                                                           |
| 5            | IDVCLC-design variable control parameter<br>If (IDVCLC.EQ.1) NDV=NDVAR1<br>If (IDVCLC.EQ.2) NDV=NDVAR1+ NDVAR2<br>If (IDVCLC.EQ.3) NDV=NDVAR2    |
| 6            | IRECP-reciprocal variable identifier<br>If (IRECP.GT.0) the X-vector contains<br>the reciprocal of area and VLB & VUB<br>are changed accordingly |

DATA BLOCK C

DESCRIPTION: Dynamic Analysis Information

Format and Example

| LMASS | GRAV  | EPSEIG |  | FORMAT        |
|-------|-------|--------|--|---------------|
|       |       |        |  | I5,<br>2F10.0 |
| 0     | 386.4 | 0.     |  |               |

FIELD

CONTENTS

- 1 LMASS-lumped mass option (if LMASS.NE.0)  
the lumped mass matrix is used.
- 2 GRAV-accleration due to gravity  
(default=386.4 inches/sec )
- 3 EPSEIG-convergence tolerance on eigenvalue  
solution. (default=.0001)

DATA BLOCK D

DESCRIPTION: Joint Coordinates &

Design Variable Linking

Format and Example

| JN | X | Y | Z | IX | IY | IZ | PCX | PCY | PCZ | FORMAT                           |
|----|---|---|---|----|----|----|-----|-----|-----|----------------------------------|
|    |   |   |   |    |    |    |     |     |     | I5,<br>3F10.0,<br>3I5,<br>3F10.0 |

|   |      |    |    |   |   |   |     |    |    |
|---|------|----|----|---|---|---|-----|----|----|
| 1 | -10. | 0. | 0. | 1 | 0 | 0 | -1. | 0. | 0. |
|---|------|----|----|---|---|---|-----|----|----|

|   |    |      |    |   |   |   |    |    |    |
|---|----|------|----|---|---|---|----|----|----|
| 2 | 0. | -10. | 0. | 0 | 0 | 0 | 0. | 0. | 0. |
|---|----|------|----|---|---|---|----|----|----|

|   |    |    |    |   |   |   |    |    |    |
|---|----|----|----|---|---|---|----|----|----|
| 3 | 0. | 0. | 0. | 0 | 0 | 0 | 0. | 0. | 0. |
|---|----|----|----|---|---|---|----|----|----|

|   |     |    |    |   |   |   |    |    |    |
|---|-----|----|----|---|---|---|----|----|----|
| 4 | 10. | 0. | 0. | 1 | 0 | 0 | 1. | 0. | 0. |
|---|-----|----|----|---|---|---|----|----|----|

FIELD

CONTENTS

- |    |                                             |
|----|---------------------------------------------|
| 1  | JN-joint coordinate number                  |
| 2  | X-x coordinate                              |
| 3  | Y-y coordinate                              |
| 4  | Z-z coordinate                              |
| 5  | IX-design variable associated with x coord. |
| 6  | IY-design variable associated with y coord. |
| 7  | IZ-design variable associated with z coord. |
| 8  | PCX-participation coefficient of x-coord.   |
| 9  | PCY-participation coefficient of y-coord.   |
| 10 | PCZ-participation coefficient of z-coord.   |

NOTE: Number of cards read=NJ

DATA BLOCK E

DESCRIPTION: Material Properties

Format and Example

| E        | RHO | SIGMIN  | SIGMAX | KEULER | FORMAT |
|----------|-----|---------|--------|--------|--------|
|          |     |         |        |        | 5F10.0 |
| 1000000. | .1  | -15000. | 20000. | 4.     |        |

FIELD

CONTENTS

- |   |                                                      |
|---|------------------------------------------------------|
| 1 | E-Young's Modulus                                    |
| 2 | RHO-material density                                 |
| 3 | SIGMIN-minimum allowable stress                      |
| 4 | SIGMAX-maximum allowable stress                      |
| 5 | KEULER-Euler buckling coefficient<br>for bar element |

NOTE: Number of cards read=NMT

DATA BLOCK F

DESCRIPTION: Bar Element Information

Format and Example

| ELNO | NODE1 | NODE2 | MATCOD | NDSG | A | FORMAT    |
|------|-------|-------|--------|------|---|-----------|
|      |       |       |        |      |   | 5I5,F10.0 |

|   |   |   |   |   |    |
|---|---|---|---|---|----|
| 1 | 1 | 2 | 1 | 1 | 1. |
|---|---|---|---|---|----|

|   |   |   |   |   |    |
|---|---|---|---|---|----|
| 2 | 3 | 2 | 1 | 2 | 1. |
|---|---|---|---|---|----|

|   |   |   |   |   |    |
|---|---|---|---|---|----|
| 3 | 4 | 2 | 1 | 1 | 1. |
|---|---|---|---|---|----|

FIELD

CONTENTS

- |   |                                                             |
|---|-------------------------------------------------------------|
| 1 | ELNO-element number                                         |
| 2 | NODE1-global number associated with<br>element node         |
| 3 | NODE2-global number associated with<br>element node         |
| 4 | MATCOD-material type of this element                        |
| 5 | NDSG-design variable number associated<br>with this element |
| 6 | A-member cross-sectional area                               |

NOTE: Number of cards read=NE

DATA BLOCK G

DESCRIPTION: Joint Constraint Information

Format and Example

| JN | IX | IY | IZ |  | FORMAT |
|----|----|----|----|--|--------|
|    |    |    |    |  | 4I5    |

|   |   |   |   |  |
|---|---|---|---|--|
| 1 | 1 | 1 | 1 |  |
|---|---|---|---|--|

|   |   |   |   |  |
|---|---|---|---|--|
| 2 | 0 | 0 | 1 |  |
|---|---|---|---|--|

|   |   |   |   |  |
|---|---|---|---|--|
| 3 | 1 | 1 | 1 |  |
|---|---|---|---|--|

|   |   |   |   |  |
|---|---|---|---|--|
| 4 | 1 | 1 | 1 |  |
|---|---|---|---|--|

FIELD

CONTENTS

- |   |                                             |
|---|---------------------------------------------|
| 1 | JN-joint number                             |
| 2 | IX x,y,z constraint identifier. (if non-    |
| 3 | IY zero the corresponding degree of freedom |
| 4 | IZ is constrained)                          |

NOTE: Number of cards read=NCJ

DATA BLOCK H

OMIT this card if NLC=0 was read in block B.

DESCRIPTION: Joint Loading Information

Format and Example

|     |  |              |
|-----|--|--------------|
| NLJ |  | FORMAT<br>I5 |
|-----|--|--------------|

|   |  |
|---|--|
| 1 |  |
|---|--|

|   |  |
|---|--|
| 1 |  |
|---|--|

|    |    |    |    |  |                     |
|----|----|----|----|--|---------------------|
| JN | FX | FY | FZ |  | FORMAT<br>I5,3F10.0 |
|----|----|----|----|--|---------------------|

|   |        |         |    |  |
|---|--------|---------|----|--|
| 2 | 14140. | -14140. | 0. |  |
|---|--------|---------|----|--|

|   |         |         |    |  |
|---|---------|---------|----|--|
| 2 | -14140. | -14140. | 0. |  |
|---|---------|---------|----|--|

FIELD

CONTENT

|   |                                                        |
|---|--------------------------------------------------------|
| 1 | NLJ-number of loaded joints<br>for this load condition |
| 1 | JN-joint number                                        |
| 2 | FX                                                     |
| 3 | FY- Forces in the X,Y,Z directions                     |
| 4 | FZ                                                     |

DATA BLOCK I

OMIT this block if NPMASS=0 was read in block B.

DESCRIPTION: Lumped Mass Information

Format and Example

| JN | MASS |  | FORMAT   |
|----|------|--|----------|
|    |      |  | I5,F10.0 |

|   |      |  |
|---|------|--|
| 2 | 500. |  |
|---|------|--|

FIELD

CONTENTS

- |   |                                                                |
|---|----------------------------------------------------------------|
| 1 | JN-joint number                                                |
| 2 | MASS-concentrated mass at joint (JN)<br>mass is in force units |

DATA BLOCK J

OMIT this block if NDVAR1=0

DESCRIPTION: Design Variable Information  
(AREA Variables)

Format and Example

|        |     |  |  |                  |
|--------|-----|--|--|------------------|
| XA (I) |     |  |  | FORMAT<br>8F10.0 |
| 1.     | 1.  |  |  |                  |
| .01    | .01 |  |  | XAL(I)           |
| 10.    | 10. |  |  | XAU(I)           |

FIELD

CONTENTS

- |   |                                           |
|---|-------------------------------------------|
| 1 | XA-initial value of area design variables |
| 2 | XAL-lower bounds on area design variables |
| 3 | XAU-upper bounds on area design variables |

NOTE: read one value of XA, XAL, XAU for each  
independent area variable defined in Block D

Number of cards read =as required

DATA BLOCK K

OMIT this block if NDVAR2=0

DESCRIPTION: Design Variable Information  
(COORDINATE Variables)

Format and Example

| XC (1) | XC (2) | . . . . | XC (NDVAR1) | FORMAT |
|--------|--------|---------|-------------|--------|
|        |        |         |             | 8F10.0 |
| 10.    |        |         |             |        |
| 1.0    |        |         |             | XCL    |
| 20.    |        |         |             | XCX    |

FIELD

CONTENTS

- |   |                                             |
|---|---------------------------------------------|
| 1 | XC-initial value of coord. design variables |
| 2 | XCL-lower bounds on coord. design variables |
| 3 | XCX-upper bounds on coord. design variables |

NOTE: read one value of XC, XCL, XCX for  
each independent coordinate variable  
defined in Block D

Number of cards read =as required.

DATA BLOCK L

OMIT this block if NDSPLC=0 in Block A

DESCRIPTION: Joint Displacement Constraint Information

Format and Example

| JN | DIR | LC | BL | BU |  | FORMAT     |
|----|-----|----|----|----|--|------------|
|    |     |    |    |    |  | 3I5,2F10.0 |

|   |   |   |      |     |  |
|---|---|---|------|-----|--|
| 2 | 1 | 1 | -.02 | .02 |  |
|---|---|---|------|-----|--|

|   |   |   |      |     |  |
|---|---|---|------|-----|--|
| 2 | 2 | 1 | -.02 | .02 |  |
|---|---|---|------|-----|--|

FIELD

CONTENTS

- |   |                                                          |
|---|----------------------------------------------------------|
| 1 | JN-joint number                                          |
| 2 | DIR-direction 1=X 2=Y 3=z<br>0=limit on resultant displ. |
| 3 | LC-load condition                                        |
| 4 | BL-lower bound on displacement<br>(If DIR=0 read 0 here) |
| 5 | BU-upper bound on displacement                           |

Number of cards read= NDSPLC

DATA BLOCK M

OMIT this block if NFREQ=0 was read in Block A

DESCRIPTION: Frequency Constraint Information

Format and Example

|     |     |     |       |      |  |                  |
|-----|-----|-----|-------|------|--|------------------|
| FC1 | FC2 | FC3 | ..... | .FCN |  | FORMAT<br>8F10.0 |
| 20. |     |     |       |      |  |                  |

FIELD

CONTENTS

- |   |                                                                                       |
|---|---------------------------------------------------------------------------------------|
| 1 | FC1- lower bound on first natural frequency constraint in CPS. (cycles per second)    |
| N | FCN- lower bound on NFREQ-th natural frequency constraint in CPS. (cycles per second) |

NOTE: OMIT this block if NFREQ=0 was read in data block B.

Number of cards read= as required

## VI. NUMERICAL EXAMPLES

### A. INTRODUCTION

Design of planar trusses and 3-dimensional space towers are presented here and the corresponding numerical results are summarized to demonstrate the use of the code.

In the examples given here, the design variables are member cross-sectional areas and joint coordinates. It should be emphasized that in practical design, the reciprocal of the member areas is usually a better choice for the design variables. However, the purpose here is to knowingly create difficult optimization problems, thus the choice of variables.

The examples begin with the 3-bar truss.

### B. CASE 1: 3-BAR PLANAR TRUSS

The simple 3-bar planar truss, as shown in Figure 6.1 has been previously used for the user guide example. This structure was designed for optimum geometry subject to a set of two load conditions, buckling constraints, displacement constraints, and a lower bound on the system's first natural frequency. The allowable stresses specified are

$$-15000. < \sigma_i < 20000. \text{ psi} \quad i=1,3$$

The member areas were linked in the following groups: A1=A3;  
A2.

1. Case 1a

Only the stress constraint was imposed for this case. Final design information is given in Table VI. The number of analysis for this design was 38.

2. Case 1b

This case includes the previous constraint plus constraints on buckling ( $KEULER=4.0$ ), displacement ( $-.02$   $-.02$  in.), and first natural frequency ( $\omega_n=20.0$ ). Results are given in Table VII. The number of analysis required for this design was 16 with 1.73 seconds of CPU time.

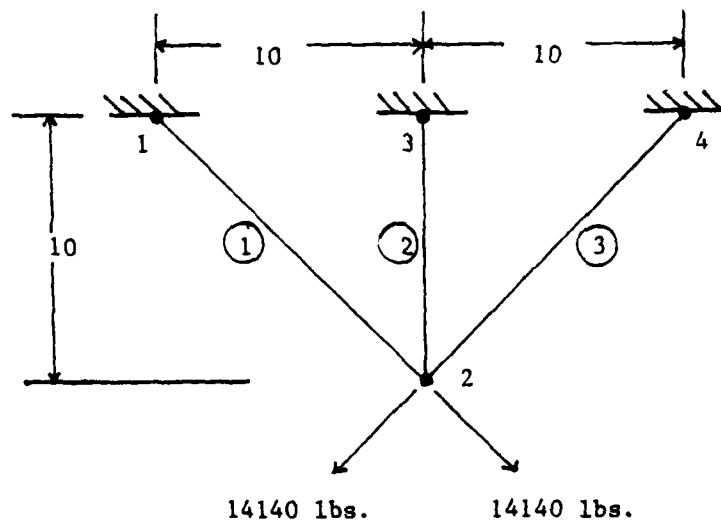


Figure 6.1 3-BAR TRUSS

C. CASE 2: 18-BAR PLANAR TRUSS

A cantiliver truss, as shown in Figure 6.2, has been previously used as a standard test case for structural design [Ref. 2]. The structure was analyzed for a single set of load conditions with allowable stresses being

$$-20000. < \sigma_i < 20000. \text{ psi} \quad i=1,18$$

Young's modulus was taken as  $10^7$  psi with a material density  $\rho=0.1$  lb./cu in.

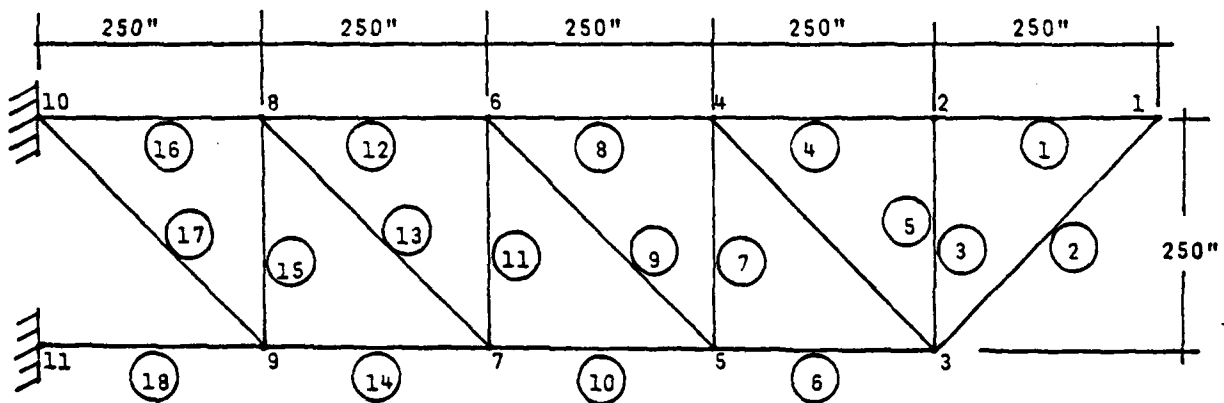


Figure 6.2 18-BAR TRUSS

The independent coordinate variables were taken as  $X_3, Y_3, X_5, Y_5, X_7, Y_7, X_9, Y_9$ . The member areas were linked as follows:  $A_1=A_4=A_8=A_{12}=A_{16}$ ;  $A_2=A_6=A_{10}=A_{14}=A_{18}$ ;  $A_3=A_7=A_{11}=A_{15}$ ;  $A_5=A_9=A_{13}=A_{17}$ . There are a total of four independent area variables and eight coordinate variables.

#### 1. Case 2a

This design analysis includes stress, buckling (KEULER=4.0), displacement (-10.0 to 10.0 in.), and a first fundamental frequency of 3 Hz. Additionally, a nonstructural mass of  $W=5000$  lbs. was attached to node 1. The number of analyses for this design was 62. Results are presented in Table VIII. 26.72 seconds of CPU time were used for this calculation.

#### D. CASE 3: 25-BAR SPACE TOWER

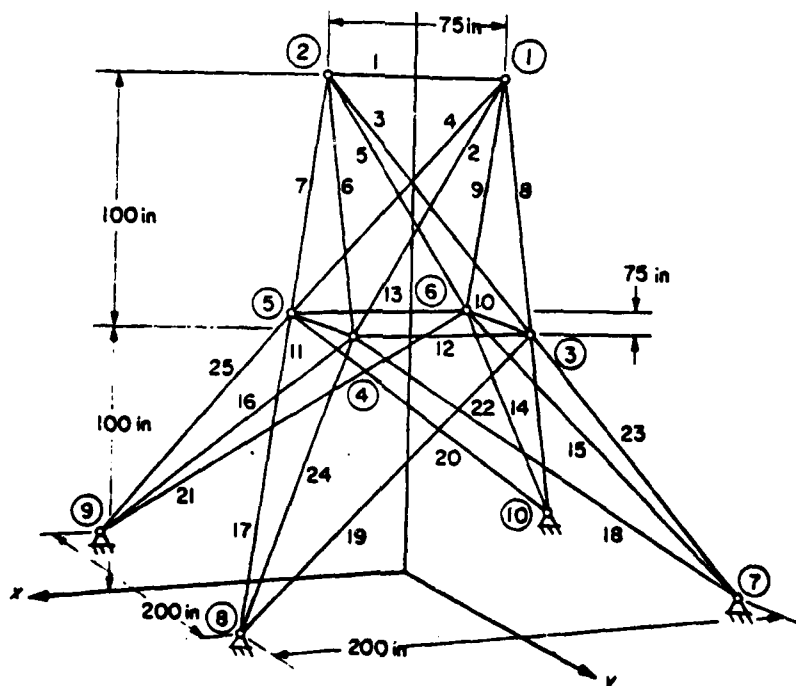


Figure 6.3 25-BAR SPACE TOWER

The 25-bar space tower shown in Figure 6.3 was designed for two independent load conditions given in Table X. The allowable stresses were specified as follows

$$-40000. < \sigma_i < 40000. \text{ psi} \quad i=1,25$$

Young's modulus was selected as  $10^7$  psi with a material density  $\rho = .1$  lb/cu. in. Members are assumed tubular with a nominal diameter to thickness ratio of  $D/t=100$  giving  $KEULER=39.274$ . Symmetry was imposed in both the x-z and y-z planes. Non-structural masses of  $W=500$  lbs. were attached at nodes 1 and 2. Coordinate variables were  $X4, Y4, Z4, X8$ , and  $Y8$  with the remaining coordinates linked to maintain symmetry. Area variables were linked in the following manner:  $A1; A2=A3=A4=A5; A6=A7=A8=A9; A10=A11; A12=A13; A14=A15=A16=A17; A18=A19=A20=A21; A22=A23=A24=A25$ .

#### 1. Case 3a

Stress, displacement ( $-0.35$  to  $0.35$  in.), Euler buckling and first natural frequency limited to a value  $\omega_n > 16$  Hz. were imposed for this case. Final design information is given in Table XI. The number of analyses for this design was 61 with 27.99 seconds of CPU time used.

#### E. CASE 4: 234-BAR SPACE TOWER

The initial layout of the tower is shown in Figure 6.4 stress limits were as follows

$$-15000. < \sigma_i < 20000. \text{ psi} \quad i=1,234$$

Young's modulus was chosen as steel  $3 \times 10^7$  psi with a material density of aluminum  $\rho = .1$  lbs/cu. in.

1. Case 4a

Stress constraints as well as constraints on Euler buckling were imposed. The resulting problem had 56 area design variables and 42 coordinate variables. This problem required 91 structural analyses using 72 minutes of CPU time. The objective function was evaluated 89 times and gradients were calculated 30 times. Results are presented in Tables XII through XIV. Although the weight of the structure was only reduced by 2%, it should be noted that constraints were initially violated and the optimizer overcame the constraint violations. It is believed the optimum that was reached is not the true optimum because of the extreme non-linearity of the problem.

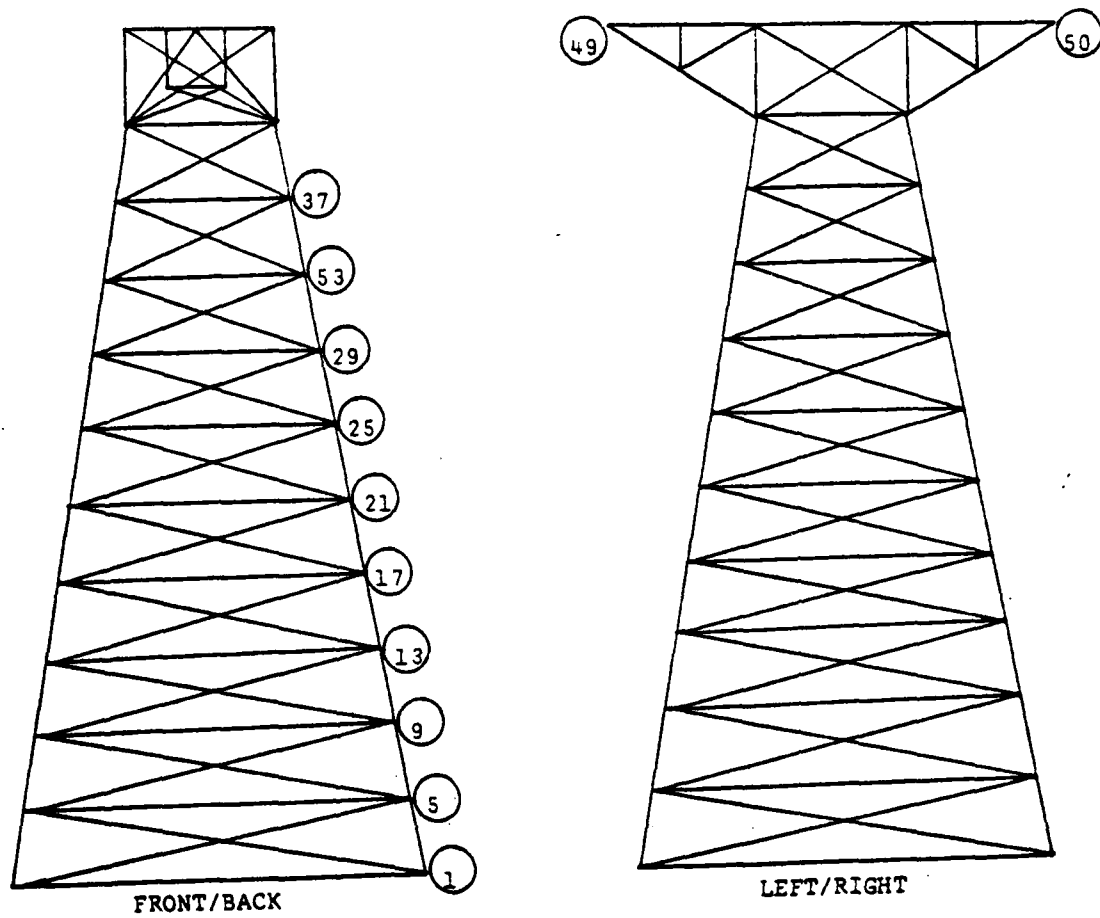


Figure 6.4 234-BAR SPACE TOWER

Table VI

3-BAR TRUSS. DESIGN INFORMATION (STRESS)

BODY

| <u>LOAD<br/>COND.</u> | <u>JOINT</u> | X           | <u>LOADS<br/>Y</u> | Z   |
|-----------------------|--------------|-------------|--------------------|-----|
| 1                     | 2            | 0.1414E+05  | -0.1414E+05        | 0.0 |
| 2                     | 2            | -0.1414E+05 | -0.1414E+05        | 0.0 |

FIXED MASSES

| NO. | JOINT | MASS     |
|-----|-------|----------|
| 1   | 2     | 500 lbs. |

AREA (sq. in.)

| MEMBER | INITIAL | FINAL     |
|--------|---------|-----------|
| A1=A3  | 1.0     | .7662E+00 |
| A2     | 1.0     | .4833E+00 |

COORDINATES (in.)

| JOINT | INITIAL | FINAL     |
|-------|---------|-----------|
| 2     | 10      | .9856E+01 |

FINAL WEIGHT FOR AREA AND COORDINATES

WEIGHT = 2.6349 (lbs.)

Table VII

3-BAR TRUSS. DESIGN INFORMATION  
(STRESS, DISPLACEMENT, BUCKLING, FREQUENCY)

BODY

JOINT LOADING INFORMATION

SAME AS TABLE VI

JOINT DISPLACEMENT INFORMATION

| JOINT<br>NUMBER | DIR. | LOAD<br>COND. | LOWER<br>BOUND | UPPER<br>BOUND |
|-----------------|------|---------------|----------------|----------------|
| 2               | 1    | 1             | -.02           | .02            |
| 2               | 2    | 1             | -.02           | .02            |

AREA (sq. in.)

| MEMBER | INITIAL | FINAL       |
|--------|---------|-------------|
| A1=A3  | 1.0     | 0.99995E+00 |
| A2     | 1.0     | 0.1000 E-01 |

COORDINATES (in.)

| JOINT | INITIAL | FINAL       |
|-------|---------|-------------|
| 2     | 10.0    | 0.99986E+01 |

FINAL WEIGHT = 2.9381 (lbs.)

CRITICAL CONSTRAINT - FREQUENCY

Table VIII  
18-BAR TRUSS. LOAD CONDITIONS

BODY

| LOAD COND. | JOINT | <u>LOAD CONDITIONS (lbs.)</u> |             |     |
|------------|-------|-------------------------------|-------------|-----|
|            |       | X                             | LOADS<br>Y  | Z   |
| 1          | 1     | 0.0                           | -0.2000E+05 | 0.0 |
| 1          | 2     | 0.0                           | -0.2000E+05 | 0.0 |
| 1          | 4     | 0.0                           | -0.2000E+05 | 0.0 |
| 1          | 6     | 0.0                           | -0.2000E+05 | 0.0 |
| 1          | 8     | 0.0                           | -0.2000E+05 | 0.0 |

FIXED MASS INFORMATION

| NO. | JOINT | MASS        |
|-----|-------|-------------|
| 1   | 1     | 5000 (lbs.) |

Table IX

18-BAR TRUSS. DESIGN INFORMATION  
(STRESS, DISPLACEMENT, EULER BUCKLING, FREQUENCY)

| MEMBER            | <u>AREA (sq. in.)</u> |       |
|-------------------|-----------------------|-------|
|                   | INITIAL               | FINAL |
| A1=A4=A8=A12=A16  | 10.0                  | 38.20 |
| A2=A6=A10=A14=A18 | 10.0                  | 38.27 |
| A3=A7=A11=A15     | 10.0                  | 15.98 |
| A4=A9=A13=A17     | 10.0                  | 20.62 |

| JOINT | <u>COORDINATES (in.)</u> |    |       |    |
|-------|--------------------------|----|-------|----|
|       | INITIAL                  |    | FINAL |    |
|       | X                        | Y  | X     | Y  |
| 3     | 1000.                    | 0. | 639.  | 0. |
| 5     | 750.                     | 0. | 628.  | 0. |
| 7     | 500.                     | 0. | 384.  | 0. |
| 9     | 250.                     | 0. | 148.  | 0. |

FINAL WEIGHT = 13,940 (lbs.)

CRITICAL CONSTRAINT - FREQUENCY

Table X  
25-BAR TRUSS. LOAD CONDITIONS

BODY

| LOAD COND. | JOINT | <u>LOAD CONDITIONS (lbs.)</u> |            |        |
|------------|-------|-------------------------------|------------|--------|
|            |       | X                             | LOADS<br>Y | Z      |
| 1          | 1     | 0.0                           | 2000.      | -5000. |
|            | 2     | 0.0                           | -2000.     | -5000. |
| 2          | 1     | 1000.                         | 10000.     | -5000. |
|            | 2     | 0.                            | 10000.     | -5000. |
|            | 3     | 500.                          | 0.         | 0.     |
|            | 6     | 500.                          | 0.         | 0.     |

FIXED MASS INFORMATION

| NO. | JOINT | MASS       |
|-----|-------|------------|
| 2   | 1     | 500.(lbs.) |
|     | 2     | 500.(lbs.) |

Table XI  
25-BAR TRUSS. DESIGN INFORMATION  
(STRESS, DISPLACEMENT, EULER BUCKLING, FREQUENCY)

| MEMBER          | <u>AREA (sq. in.)</u> |  |  |       |  |  |
|-----------------|-----------------------|--|--|-------|--|--|
|                 | INITIAL               |  |  | FINAL |  |  |
| A1              | 2.0                   |  |  | 1.46  |  |  |
| A2=A3=A4=A5     | 2.0                   |  |  | 0.74  |  |  |
| A6=A7=A8=A9     | 2.0                   |  |  | 0.98  |  |  |
| A10=A11         | 2.0                   |  |  | 1.04  |  |  |
| A12=A13         | 2.0                   |  |  | 1.12  |  |  |
| A14=A15=A16=A17 | 2.0                   |  |  | 0.74  |  |  |
| A18=A19=A20=A21 | 2.0                   |  |  | 0.86  |  |  |
| A22=A23=A24=A25 | 2.0                   |  |  | 0.70  |  |  |

| JOINT | <u>COORDINATES (in.)</u> |       |     |       |      |       |
|-------|--------------------------|-------|-----|-------|------|-------|
|       | INITIAL                  |       |     | FINAL |      |       |
|       | X                        | Y     | Z   | X     | Y    | Z     |
| 4     | 37.5                     | 37.5  | 100 | 39.4  | 46.9 | 138.9 |
| 8     | 100.0                    | 100.0 | 0.0 | 73.6  | 68.3 | 0.0   |

FINAL WEIGHT = 267 (lbs.)

CRITICAL CONSTRAINT - FREQUENCY

Table XII

## 234-BAR SPACE TOWER. LOADING INFORMATION

BODY

| LOAD COND. | JOINT | <u>LOAD CONDITIONS (lbs.)</u> |            |        |
|------------|-------|-------------------------------|------------|--------|
|            |       | X                             | LOADS<br>Y | Z      |
| 1          | 49    | 6000.                         | -20000.    | 0.0    |
| 1          | 50    | 6000.                         | -20000.    | 0.0    |
| 2          | 49    | 6000.                         | -20000.    | 0.0    |
| 2          | 50    | -6000.                        | -20000.    | 0.0    |
| 3          | 49    | 6000.                         | -20000.    | 0.0    |
| 3          | 50    | 3000.                         | -10000.    | 5000.  |
| 4          | 49    | 3000.                         | -10000.    | -5000. |
| 4          | 50    | 3000.                         | -10000.    | 5000.  |
| 5          | 49    | -3000.                        | 10000.     | 5000.  |
| 5          | 50    | -3000.                        | 10000.     | -5000. |

FIXED MASS INFORMATION

| NO. | JOINT | MASS       |
|-----|-------|------------|
| 1   | 49    | 200.(lbs.) |
| 2   | 50    | 200.(lbs.) |

Table XIII

## 234-BAR SPACE TOWER. DESIGN INFORMATION

| <u>AREA (sq. in.)</u>                   |         |       |
|-----------------------------------------|---------|-------|
| MEMBER                                  | INITIAL | FINAL |
| A1,A2,A3,A4                             | 25.0    | 25.38 |
| A5,A6,A7,A8                             | 25.0    | 25.35 |
| A9,A10,A11,A12                          | 25.0    | 25.28 |
| Ak3,A14,A15,A16                         | 25.0    | 25.21 |
| A17,A18,A19,A20                         | 25.0    | 25.14 |
| A21,A22,A23,A24                         | 25.0    | 25.07 |
| A25,A26,A27,A28                         | 25.0    | 25.00 |
| A29,A30,A31,A32                         | 25.0    | 24.95 |
| A33,A34,A35,A36                         | 25.0    | 24.89 |
| A37,A38,A39,A40                         | 25.0    | 24.85 |
| A41,A42,A43,A44                         | 25.0    | 24.98 |
| A45,A46,A47,A48                         | 25.0    | 24.87 |
| A49,A50,A51,A52                         | 25.0    | 24.88 |
| A53,A54,A55,A56                         | 25.0    | 24.89 |
| A57,A58,A59,A60                         | 25.0    | 24.89 |
| A61,A62,A63,A64                         | 25.0    | 24.90 |
| A65,A66,A67,A68                         | 25.0    | 24.91 |
| A69,A70,A71,A72                         | 25.0    | 24.91 |
| A73,A74,A75,A76                         | 25.0    | 24.91 |
| A77,A78,A79,A80                         | 25.0    | 24.91 |
| A81,A83                                 | 25.0    | 24.96 |
| A82,A84                                 | 25.0    | 24.96 |
| A85,A87                                 | 25.0    | 24.96 |
| A86,A88                                 | 25.0    | 24.95 |
| A89,A90,A91,A92,A93,A94,A95,A96         | 25.0    | 24.68 |
| A97,A98,A99,A100,A101,A102,A103,A104    | 25.0    | 24.69 |
| A150,A106,A107,A108,A109,A110,A111,A112 | 25.0    | 24.71 |
| A113,A114,A115,A116,A117,A118,A119,A120 | 25.0    | 24.73 |
| A121,A122,A123,A124,A125,A126,A127,A128 | 25.0    | 24.74 |
| A129,A130,A131,A132,A133,A134,A135,A136 | 25.0    | 24.75 |
| A137,A138,A139,A140,A141,A142,A143,A144 | 25.0    | 24.74 |
| A145,A146,A147,A148,A149,A150,A151,A152 | 25.0    | 24.72 |
| A153,A154,A155,A156,A157,A158,A159,A160 | 25.0    | 24.69 |
| A161,A162,A163,A164,A165,A166,A167,A168 | 25.0    | 24.65 |
| A169,A170,A171,A172,A173,A174,A175,A176 | 25.0    | 24.82 |
| A177,A178,A179,A180                     | 25.0    | 24.96 |
| A181,A182,A183,A184                     | 25.0    | 24.96 |
| A185,A186,A187,A188                     | 25.0    | 24.87 |
| A189,A190,A191,A192                     | 25.0    | 24.86 |

Table XIII (cont'd)

| MEMBER              | <u>AREA (sq. in.)</u> |       |
|---------------------|-----------------------|-------|
|                     | INITIAL               | FINAL |
| A193,A194,A195,A196 | 25.0                  | 24.95 |
| A197,A198,A199,A200 | 25.0                  | 24.97 |
| A201,A202           | 25.0                  | 24.91 |
| A203,A204           | 25.0                  | 24.92 |
| A205,A206,A207,A208 | 25.0                  | 24.86 |
| A209,A210,A211,A212 | 25.0                  | 24.87 |
| A213,A214           | 25.0                  | 24.89 |
| A215,A216           | 25.0                  | 24.90 |
| A217,A218           | 25.0                  | 24.91 |
| A219,A220           | 25.0                  | 24.92 |
| A221,A222           | 25.0                  | 24.92 |
| A223,A224           | 25.0                  | 24.93 |
| A225,A226           | 25.0                  | 24.93 |
| A227,A228           | 25.0                  | 24.94 |
| A229,A230           | 25.0                  | 24.94 |
| A231,A232           | 25.0                  | 24.94 |
| A233,A234           | 25.0                  | 24.93 |

| JOINT | <u>COORDINATES (in.)</u> |              |     |       |            |       |
|-------|--------------------------|--------------|-----|-------|------------|-------|
|       | X                        | INITIAL<br>Y | Z   | X     | FINAL<br>Y | Z     |
| 1     | 120                      | 0*           | 120 | 120.5 | 0          | 121.4 |
| 5     | 111                      | 120          | 111 | 110.7 | 120.4      | 112.1 |
| 9     | 102                      | 240          | 102 | 102.2 | 241.2      | 103.2 |
| 13    | 93                       | 360          | 93  | 93.1  | 362.6      | 93.7  |
| 17    | 84                       | 480          | 84  | 84.0  | 483.8      | 84.4  |
| 21    | 75                       | 600          | 75  | 74.9  | 604.5      | 75.2  |
| 25    | 66                       | 720          | 66  | 65.9  | 724.2      | 65.9  |
| 29    | 57                       | 840          | 57  | 56.8  | 842.6      | 56.8  |
| 33    | 48                       | 960          | 48  | 47.8  | 960.4      | 47.3  |

Initial weight = 84,524 lbs.      Final weight = 83,142 lbs.

\*Final weight (AREA VARIABLES ONLY) = 28,900 lbs.

\* This clearly indicates optimum not reached with previous case.

Table XIII (cont'd)

| JOINT | <u>COORDINATES (in.)</u> |              |    |      |            |      |
|-------|--------------------------|--------------|----|------|------------|------|
|       | X                        | INITIAL<br>Y | Z  | X    | FINAL<br>Y | Z    |
| 37    | 39                       | 1080         | 39 | 38.8 | 1077.4     | 38.8 |
| 41    | 30                       | 0*           | 30 | 29.9 | -          | 29.9 |
| 45    | 30                       | 1248         | 30 | 29.8 | 1212.0     | 29.9 |
| 49    | 0*                       | 1248         | 90 | -    | 1203.5     | 90.0 |
| 51    | 15                       | 1224         | 60 | 15.0 | 1194.1     | 58.9 |
| 53    | 15                       | 1248         | 60 | 15.0 | 1214.7     | 59.2 |

\*NOT A DESIGN VARIABLE

## VII. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

The finite element code was presented coupled to an optimizer for truss analysis and design. Trusses were designed for minimum weight with multiple load conditions considered.

The displacement method for static analysis and the subspace iteration method for eigenvalues were applied.

Several examples were considered. In every case the code worked as an analysis tool, and significant weight reductions were obtained with the coupled optimizer CONMIN. Run times and results compared to the same test cases with other codes indicate that the code is competitive as a design tool.

### B. RECOMMENDATIONS

The following recommendations may be of value for follow on work:

1. The code should be modified so the user can access stresses directly.
2. The code should be extended to include other elements such as frames and plates.
3. An out of core equation solver should be added.
4. The method of gradient calculation should be dependent on specific gradients required reference 3 and reference 4.

5. Gradients of frequency constraints would benefit from a more efficient algorithm reference 5.
6. The need for a large scale public structural optimization code still exists.

## APPENDIX A

### DATA FILES

#### A. INTRODUCTION

This appendix contains the data files used to create the test cases in Chapter VI. Additionally the data file for the user's guide in complete form is presented.

(STRESS)

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DATA FILE 3-BAR TRUSS

```

3- BAR TRUSS (TEST CASE D-STRESS, DISPL., BUCKL., FREQ. 1
3      2      4      1      2      1      2      0
2      0      1      1      2      1      0
0      0      0      0      0      0      0
1      0      0      0      0      0      0
2      0      0      0      0      0      0
3      0      0      0      0      0      0
4      0      0      0      0      0      0
10000000.      .1      -15000.      20000.      4.
1      1      1      1      1      1
2      3      4      2      1      1
3      1      1      1      1      1
1      0      1      1      1      1
2      1      1      1      1      1
3      1      1      1      1      1
4      1      1      1      1      1
1      14140.      -14140.      0.
2      1      1      1      1      1
1      -14140.      -14140.      0.
2      500.
2      1.
1.      .01
.01      .01
10.      10.
10.      10.
1.0      1.0
20.      20.
2      2      1      -.02      .02
2      2      1      -.02      .02
20.

```

Table XVI

## DATA FILE 18-BAR TRUSS

(STRESS, DISPLACEMENT, BUCKLING, FREQUENCY)

| 18-BAR TRUSS CASE (TEST CASE STRESS/DISP./BUCKLING/FREQ.) |    |    |    |   |   |   |   |  |  |
|-----------------------------------------------------------|----|----|----|---|---|---|---|--|--|
| 18                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 19                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 20                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 21                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 22                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 23                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 24                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 25                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 26                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 27                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 28                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 29                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 30                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 31                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 32                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 33                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 34                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 35                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 36                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 37                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 38                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 39                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 40                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 41                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 42                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 43                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 44                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 45                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 46                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 47                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 48                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 49                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 50                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 51                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 52                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 53                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 54                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 55                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 56                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 57                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 58                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 59                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 60                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 61                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 62                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 63                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 64                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 65                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 66                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 67                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 68                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 69                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 70                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 71                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 72                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 73                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 74                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 75                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 76                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 77                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 78                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 79                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 80                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 81                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 82                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 83                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 84                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 85                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 86                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 87                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 88                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 89                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 90                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 91                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 92                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 93                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 94                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 95                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 96                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 97                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 98                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 99                                                        | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 100                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 101                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 102                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 103                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 104                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 105                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 106                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 107                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 108                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 109                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 110                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 111                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 112                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 113                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 114                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 115                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 116                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 117                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 118                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 119                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 120                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 121                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 122                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 123                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 124                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 125                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 126                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 127                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 128                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 129                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 130                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 131                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 132                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 133                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 134                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 135                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 136                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 137                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 138                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 139                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 140                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 141                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 142                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 143                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 144                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 145                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 146                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 147                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 148                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 149                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 150                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 151                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 152                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 153                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 154                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 155                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 156                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 157                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 158                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 159                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 160                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 161                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 162                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 163                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 164                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 165                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 166                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 167                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 168                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 169                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 170                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 171                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 172                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 173                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 174                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 175                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 176                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 177                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 178                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 179                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 180                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 181                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 182                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 183                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 184                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 185                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 186                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 187                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 188                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 189                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 190                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 191                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 192                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 193                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 194                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 195                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 196                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 197                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 198                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 199                                                       | 11 | 11 | 11 | 1 | 1 | 1 | 0 |  |  |
| 200                                                       |    |    |    |   |   |   |   |  |  |

DATA FILE 25-BAR SPACE TOWER

25-BAR SPACE TRUSS (TEST CASE, STRESS/DISP./BUCKLING/FREQ.)

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Table XVIII

## DATA FILE 234-BAR SPACE TOWER

| 234-BAR | SPACE | TOWER | DESIGN | (TEST | CASE | STRESS, BUCK., | DISPL., | FREQ.) |
|---------|-------|-------|--------|-------|------|----------------|---------|--------|
| 234     | 58    | 4     | 1      | 1     | 20   | 0              |         |        |
| 1       | 3     | 2     | 1      | 1     | 20   | 0              |         |        |
| 2       | 386.4 |       | 0.     | 120.  | 1    | 0              | 2       | 1.     |
| 3       | 120.  |       | 0.     | -120. | 1    | 0              | 2       | -1.    |
| 4       | -120. |       | 0.0    | -120. | 1    | 0              | 2       | -1.    |
| 5       | 120.  |       | 120.   | 111.  | 3    | 4              | 5       | 1.     |
| 6       | -111. |       | 120.   | -111. | 3    | 4              | 5       | -1.    |
| 7       | 111.  |       | 120.   | -111. | 3    | 4              | 5       | -1.    |
| 8       | -111. |       | 120.   | -111. | 3    | 4              | 5       | -1.    |
| 9       | 102.  |       | 340.   | -102. | 6    | 7              | 7       | 1.     |
| 10      | -102. |       | 340.   | -102. | 6    | 7              | 7       | -1.    |
| 11      | 102.  |       | 340.   | -102. | 6    | 7              | 7       | 1.     |
| 12      | -102. |       | 340.   | -102. | 6    | 7              | 7       | -1.    |
| 13      | 93.   |       | 360.   | -93.  | 9    | 9              | 10      | 1.     |
| 14      | -93.  |       | 360.   | -93.  | 9    | 9              | 10      | -1.    |
| 15      | 93.   |       | 360.   | -93.  | 9    | 9              | 10      | 1.     |
| 16      | -93.  |       | 360.   | -93.  | 9    | 9              | 10      | -1.    |
| 17      | 84.   |       | 480.   | -84.  | 12   | 13             | 14      | 1.     |
| 18      | -84.  |       | 480.   | -84.  | 12   | 13             | 14      | -1.    |
| 19      | 84.   |       | 480.   | -84.  | 12   | 13             | 14      | 1.     |
| 20      | -84.  |       | 480.   | -84.  | 12   | 13             | 14      | -1.    |
| 21      | 75.   |       | 600.   | -75.  | 15   | 16             | 17      | 1.     |
| 22      | -75.  |       | 600.   | -75.  | 15   | 16             | 17      | -1.    |
| 23      | 75.   |       | 600.   | -75.  | 15   | 16             | 17      | 1.     |
| 24      | -75.  |       | 600.   | -75.  | 15   | 16             | 17      | -1.    |
| 25      | 66.   |       | 720.   | -66.  | 18   | 19             | 20      | 1.     |
| 26      | -66.  |       | 720.   | -66.  | 18   | 19             | 20      | -1.    |
| 27      | 66.   |       | 720.   | -66.  | 18   | 19             | 20      | 1.     |
| 28      | -66.  |       | 720.   | -66.  | 18   | 19             | 20      | -1.    |
| 29      | 57.   |       | 840.   | -57.  | 21   | 22             | 23      | 1.     |
| 30      | -57.  |       | 840.   | -57.  | 21   | 22             | 23      | -1.    |
| 31      | 57.   |       | 840.   | -57.  | 21   | 22             | 23      | 1.     |
| 32      | -57.  |       | 840.   | -57.  | 21   | 22             | 23      | -1.    |
| 33      | 48.   |       | 960.   | -48.  | 24   | 25             | 26      | 1.     |
| 34      | -48.  |       | 960.   | -48.  | 24   | 25             | 26      | -1.    |
| 35      | 48.   |       | 960.   | -48.  | 24   | 25             | 26      | 1.     |
| 36      | -48.  |       | 960.   | -48.  | 24   | 25             | 26      | -1.    |
| 37      | 39.   |       | 1080.  | -39.  | 27   | 28             | 29      | 1.     |
| 38      | -39.  |       | 1080.  | -39.  | 27   | 28             | 29      | -1.    |
| 39      | 39.   |       | 1080.  | -39.  | 27   | 28             | 29      | 1.     |
| 40      | -39.  |       | 1080.  | -39.  | 27   | 28             | 29      | -1.    |
| 41      | 30.   |       | 1200.  | -30.  | 30   | 31             | 32      | 1.     |
| 42      | -30.  |       | 1200.  | -30.  | 30   | 31             | 32      | -1.    |
| 43      | 30.   |       | 1200.  | -30.  | 30   | 31             | 32      | 1.     |
| 44      | -30.  |       | 1200.  | -30.  | 30   | 31             | 32      | -1.    |
| 45      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 46      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 47      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 48      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 49      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 50      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 51      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 52      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 53      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 54      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 55      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 56      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 57      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 58      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 59      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 60      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 61      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 62      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 63      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 64      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 65      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 66      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 67      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 68      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 69      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 70      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 71      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 72      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 73      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 74      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 75      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 76      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 77      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 78      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 79      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 80      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 81      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 82      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 83      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 84      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 85      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 86      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 87      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 88      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 89      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 90      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 91      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 92      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 93      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 94      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 95      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 96      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 97      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 98      | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |
| 99      | 30.   |       | 1248.  | -30.  | 33   | 34             | 35      | 1.     |
| 100     | -30.  |       | 1248.  | -30.  | 33   | 34             | 35      | -1.    |

Table XVIII (cont'd)

|    |    |    |   |   |      |
|----|----|----|---|---|------|
| 12 | 12 | 16 | 1 | 3 | 10.  |
| 13 | 13 | 17 | 1 | 3 | 100. |
| 14 | 14 | 18 | 1 | 3 | 100. |
| 15 | 15 | 19 | 1 | 3 | 100. |
| 16 | 16 | 20 | 1 | 3 | 100. |
| 17 | 17 | 21 | 1 | 3 | 100. |
| 18 | 18 | 22 | 1 | 3 | 100. |
| 19 | 19 | 23 | 1 | 3 | 100. |
| 20 | 20 | 24 | 1 | 3 | 100. |
| 21 | 21 | 25 | 1 | 3 | 100. |
| 22 | 22 | 26 | 1 | 3 | 100. |
| 23 | 23 | 27 | 1 | 3 | 100. |
| 24 | 24 | 28 | 1 | 3 | 100. |
| 25 | 25 | 29 | 1 | 3 | 100. |
| 26 | 26 | 30 | 1 | 3 | 100. |
| 27 | 27 | 31 | 1 | 3 | 100. |
| 28 | 28 | 32 | 1 | 3 | 100. |
| 29 | 29 | 33 | 1 | 3 | 100. |
| 30 | 30 | 34 | 1 | 3 | 100. |
| 31 | 31 | 35 | 1 | 3 | 100. |
| 32 | 32 | 36 | 1 | 3 | 100. |
| 33 | 33 | 37 | 1 | 3 | 100. |
| 34 | 34 | 38 | 1 | 3 | 100. |
| 35 | 35 | 39 | 1 | 3 | 100. |
| 36 | 36 | 40 | 1 | 3 | 100. |
| 37 | 37 | 41 | 1 | 3 | 100. |
| 38 | 38 | 42 | 1 | 3 | 100. |
| 39 | 39 | 43 | 1 | 3 | 100. |
| 40 | 40 | 44 | 1 | 3 | 100. |
| 41 | 41 | 45 | 1 | 3 | 100. |
| 42 | 42 | 46 | 1 | 3 | 100. |
| 43 | 43 | 47 | 1 | 3 | 100. |
| 44 | 44 | 48 | 1 | 3 | 100. |
| 45 | 45 | 49 | 1 | 3 | 100. |
| 46 | 46 | 50 | 1 | 3 | 100. |
| 47 | 47 | 51 | 1 | 3 | 100. |
| 48 | 48 | 52 | 1 | 3 | 100. |
| 49 | 49 | 53 | 1 | 3 | 100. |
| 50 | 50 | 54 | 1 | 3 | 100. |
| 51 | 51 | 55 | 1 | 3 | 100. |
| 52 | 52 | 56 | 1 | 3 | 100. |
| 53 | 53 | 57 | 1 | 3 | 100. |
| 54 | 54 | 58 | 1 | 3 | 100. |
| 55 | 55 | 59 | 1 | 3 | 100. |
| 56 | 56 | 60 | 1 | 3 | 100. |
| 57 | 57 | 61 | 1 | 3 | 100. |
| 58 | 58 | 62 | 1 | 3 | 100. |
| 59 | 59 | 63 | 1 | 3 | 100. |
| 60 | 60 | 64 | 1 | 3 | 100. |
| 61 | 61 | 65 | 1 | 3 | 100. |
| 62 | 62 | 66 | 1 | 3 | 100. |
| 63 | 63 | 67 | 1 | 3 | 100. |
| 64 | 64 | 68 | 1 | 3 | 100. |
| 65 | 65 | 69 | 1 | 3 | 100. |
| 66 | 66 | 70 | 1 | 3 | 100. |
| 67 | 67 | 71 | 1 | 3 | 100. |
| 68 | 68 | 72 | 1 | 3 | 100. |
| 69 | 69 | 73 | 1 | 3 | 100. |
| 70 | 70 | 74 | 1 | 3 | 100. |
| 71 | 71 | 75 | 1 | 3 | 100. |
| 72 | 72 | 76 | 1 | 3 | 100. |
| 73 | 73 | 77 | 1 | 3 | 100. |
| 74 | 74 | 78 | 1 | 3 | 100. |
| 75 | 75 | 79 | 1 | 3 | 100. |
| 76 | 76 | 80 | 1 | 3 | 100. |
| 77 | 77 | 81 | 1 | 3 | 100. |
| 78 | 78 | 82 | 1 | 3 | 100. |
| 79 | 79 | 83 | 1 | 3 | 100. |
| 80 | 80 | 84 | 1 | 3 | 100. |
| 81 | 81 | 85 | 1 | 3 | 100. |

Table XVIII (cont'd)

[illegible]

Table XVIII (cont'd)

|     |    |     |   |    |     |
|-----|----|-----|---|----|-----|
| 160 | 33 | 40  | 1 | 33 | 10. |
| 161 | 37 | 42  | 1 | 34 | 10. |
| 162 | 38 | 41  | 1 | 34 | 10. |
| 163 | 38 | 43  | 1 | 34 | 10. |
| 164 | 39 | 42  | 1 | 34 | 10. |
| 165 | 39 | 44  | 1 | 34 | 10. |
| 166 | 40 | 43  | 1 | 34 | 10. |
| 167 | 40 | 41  | 1 | 34 | 10. |
| 168 | 37 | 44  | 1 | 34 | 10. |
| 169 | 41 | 46  | 1 | 35 | 10. |
| 170 | 42 | 45  | 1 | 35 | 10. |
| 171 | 42 | 47  | 1 | 35 | 10. |
| 172 | 43 | 46  | 1 | 35 | 10. |
| 173 | 43 | 48  | 1 | 35 | 10. |
| 174 | 44 | 47  | 1 | 35 | 10. |
| 175 | 44 | 45  | 1 | 35 | 10. |
| 176 | 41 | 48  | 1 | 35 | 10. |
| 177 | 41 | 51  | 1 | 36 | 10. |
| 178 | 42 | 52  | 1 | 36 | 10. |
| 179 | 43 | 55  | 1 | 36 | 10. |
| 180 | 44 | 56  | 1 | 36 | 10. |
| 181 | 45 | 53  | 1 | 37 | 10. |
| 182 | 46 | 54  | 1 | 37 | 10. |
| 183 | 47 | 77  | 1 | 37 | 10. |
| 184 | 48 | 88  | 1 | 38 | 10. |
| 185 | 49 | 122 | 1 | 38 | 10. |
| 186 | 50 | 55  | 1 | 38 | 10. |
| 187 | 50 | 56  | 1 | 38 | 10. |
| 188 | 49 | 56  | 1 | 38 | 10. |
| 189 | 49 | 56  | 1 | 38 | 10. |
| 190 | 50 | 44  | 1 | 39 | 10. |
| 191 | 50 | 44  | 1 | 39 | 10. |
| 192 | 49 | 88  | 1 | 39 | 10. |
| 193 | 45 | 11  | 1 | 40 | 10. |
| 194 | 46 | 22  | 1 | 40 | 10. |
| 195 | 47 | 55  | 1 | 40 | 10. |
| 196 | 48 | 66  | 1 | 40 | 10. |
| 197 | 51 | 33  | 1 | 41 | 10. |
| 198 | 52 | 44  | 1 | 41 | 10. |
| 199 | 55 | 77  | 1 | 41 | 10. |
| 200 | 56 | 88  | 1 | 41 | 10. |
| 201 | 53 | 58  | 1 | 42 | 10. |
| 202 | 54 | 77  | 1 | 42 | 10. |
| 203 | 51 | 56  | 1 | 43 | 10. |
| 204 | 52 | 55  | 1 | 43 | 10. |
| 205 | 53 | 48  | 1 | 44 | 10. |
| 206 | 47 | 44  | 1 | 44 | 10. |
| 207 | 45 | 38  | 1 | 44 | 10. |
| 208 | 46 | 77  | 1 | 44 | 10. |
| 209 | 43 | 22  | 1 | 45 | 10. |
| 210 | 41 | 22  | 1 | 45 | 10. |
| 211 | 42 | 55  | 1 | 45 | 10. |
| 212 | 44 | 11  | 1 | 45 | 10. |
| 213 | 5  | 77  | 1 | 46 | 10. |
| 214 | 6  | 88  | 1 | 46 | 10. |
| 215 | 9  | 11  | 1 | 47 | 10. |
| 216 | 10 | 22  | 1 | 47 | 10. |
| 217 | 13 | 55  | 1 | 48 | 10. |
| 218 | 14 | 16  | 1 | 48 | 10. |
| 219 | 17 | 99  | 1 | 49 | 10. |
| 220 | 18 | 200 | 1 | 49 | 10. |
| 221 | 21 | 233 | 1 | 50 | 10. |
| 222 | 22 | 244 | 1 | 50 | 10. |
| 223 | 25 | 277 | 1 | 51 | 10. |
| 224 | 26 | 388 | 1 | 51 | 10. |
| 225 | 29 | 311 | 1 | 51 | 10. |
| 226 | 30 | 322 | 1 | 51 | 10. |
| 227 | 33 | 344 | 1 | 51 | 10. |
| 228 | 34 | 366 | 1 | 51 | 10. |
| 229 | 37 | 399 | 1 | 51 | 10. |
| 230 | 38 | 400 | 1 | 51 | 10. |
| 231 | 41 | 433 | 1 | 51 | 10. |
| 232 | 42 | 444 | 1 | 51 | 10. |
| 233 | 45 | 477 | 1 | 51 | 10. |

Table XVIII (cont'd)

[illegible]

Table XVIII (cont'd)

|     |   |   |   |   |
|-----|---|---|---|---|
| 50  | 2 | 2 | 1 | 1 |
| 49  | 2 | 2 | 1 | 1 |
| 50  | 2 | 2 | 1 | 1 |
| 49  | 2 | 2 | 1 | 1 |
| 50  | 2 | 2 | 1 | 1 |
| 49  | 2 | 2 | 1 | 1 |
| 50  | 2 | 2 | 1 | 1 |
| 4.5 | 2 | 2 | 1 | 1 |

## APPENDIX B

### PROGRAM ORGANIZATION

#### A. DESCRIPTION

The program organization is laid out in the following flow charts. The main driver program is arranged to call a subdriver, XMSADT, and the optimizer of the user's choice. All changes for replacing an optimizer occur in MSADT. This allows for easy testing of several optimizers on the same problem.

XMSADT may be called from the main for input, analysis, and output. Printed output may vary as the user requires. A complete listing of all subroutines and their functions is given in Table .

Table XIX  
ANALYSIS CONTROL

ANALYSIS ICALC=2

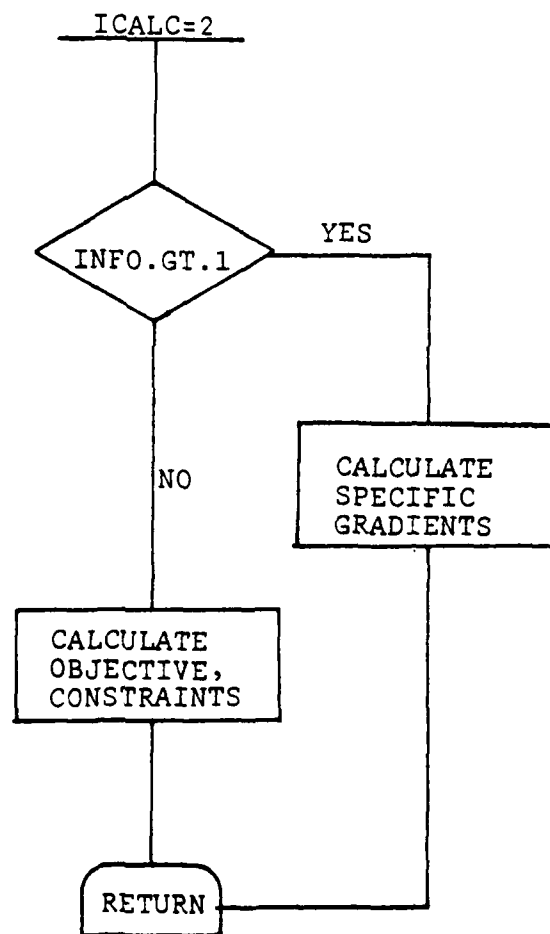


Table XX  
OUTPUT CONTROL

OUTPUT FOR INFO=0/1/2

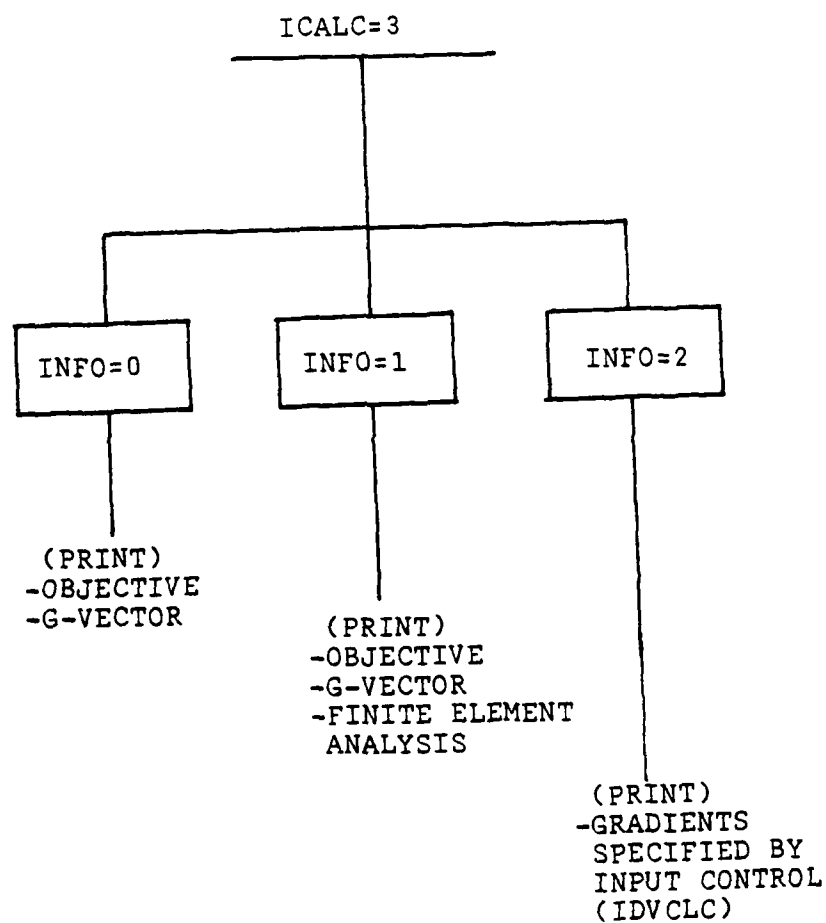


Table XXI  
PROGRAM FLOW CHART

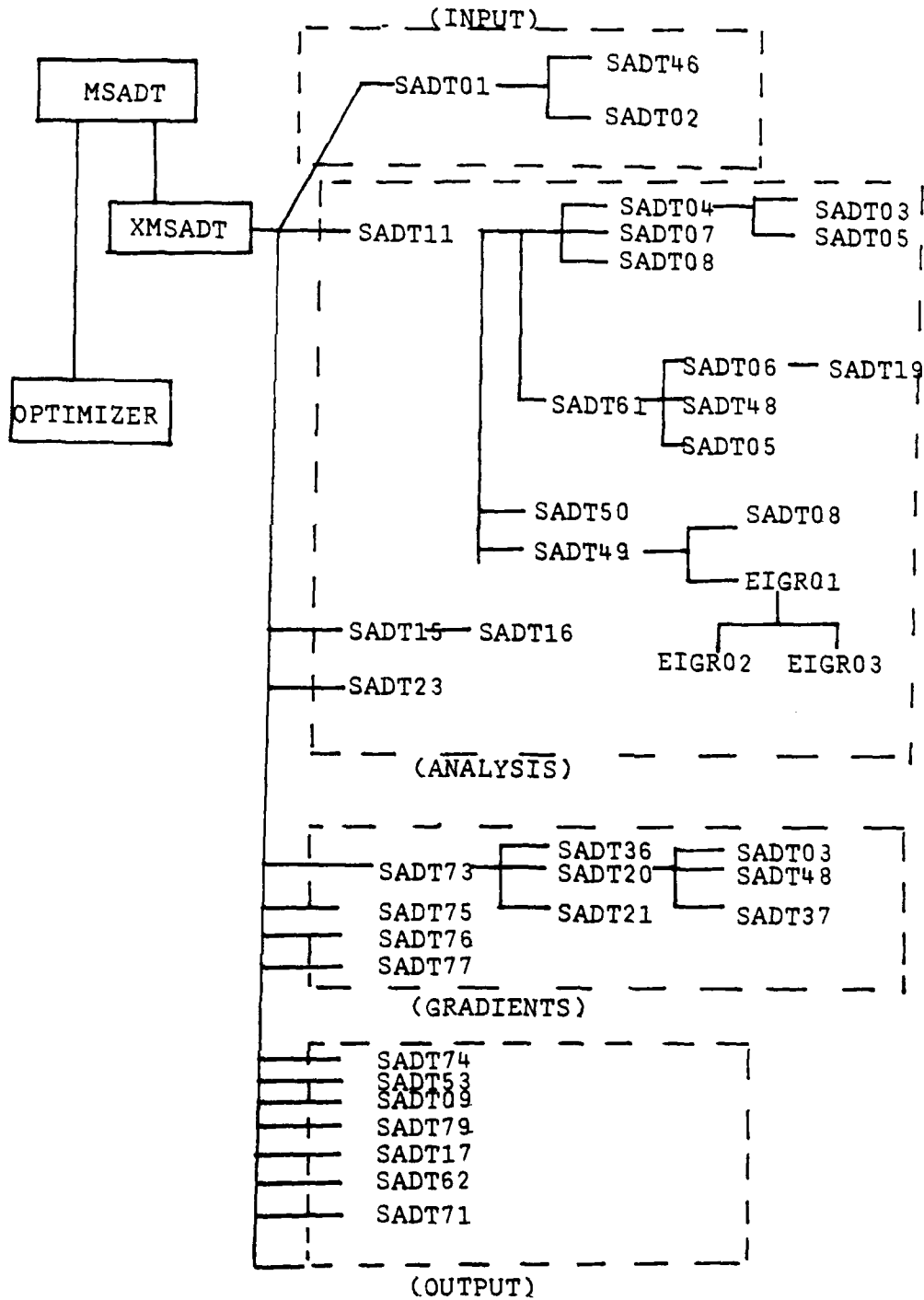


TABLE XXII  
SUBROUTINE USES

| FILENAME | TITLE                                                                                                                                                |
|----------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| EIGR01   | SOLVES EIGENVALUE PROBLEM $(A - \lambda B) X = 0$                                                                                                    |
| EIGR02   | SOLVES EIGENVALUE PROBLEM                                                                                                                            |
| EIGR03   | SOLVES EIGENVALUE PROBLEM                                                                                                                            |
| SADT01   | THIS ROUTINE READS AND PRINTS INPUT DATA<br>AND ORGANIZES PSEUDO-DYNAMIC STORAGE<br>ALLOCATION                                                       |
| SADT02   | BUILDS VECTORS JC AND IJK FOR FINITE ELEMENT<br>STRUCTURAL ANALYSIS                                                                                  |
| SADT03   | BUILDS THE ELEMENT STIFFNESS MATRIX FOR<br>TRUSS FINITE ELEMENT NO. II                                                                               |
| SADT04   | BUILDS ELEMENT STIFFNESS MATRICES AND ADDS<br>THEM TO THE GLOBAL STIFFNESS MATRIX                                                                    |
| SADT05   | SUPERIMPOSES THE ELEMENT STIFFNESS VECTOR EK<br>OF ELEMENT II ON THE GLOBAL VECTOR AK                                                                |
| SADT06   | BUILDS GLOBAL LUMPED MASS MATRIX                                                                                                                     |
| SADT07   | LU DECOMPOSES SYMMETRIC, POSITIVE-DEFINITE,<br>SPARSE MATRICES, THE UPPER TRIANGLE OF WHICH<br>IS STORED IN VECTOR AK WITH LEADING ZEROES<br>OMITTED |
| SADT08   | FORWARD AND BACK SUBSTITUTES TO YIELD A SOLN<br>TO A SET OF LINEAR EQNS (DECOMPOSED W/<br>SADT07)                                                    |
| SADT09   | PRINTS ALL JOINT DISPLACEMENTS FOR EACH<br>LOAD CONDITION OF A FINITE ELEM. STRUCTURE                                                                |
| SADT10   | PERFORMS TRUSS FIXED-GEOMETRY DESIGN                                                                                                                 |
| SADT11   | ROUTINE TO ORGANIZE ANALYSIS                                                                                                                         |
| SADT14   | CALCULATES PARTIAL DERIVATIVE OF TRUSS ELEM<br>K MATRIX WRT COORD DOF II AT NODE JI                                                                  |
| SADT15   | CALCULATES VALUES OF ALL DESIGN AND BEHAV-<br>IORIAL CONSTRAINTS AS DEFINED BY PROGRAM<br>"SAD"                                                      |
| SADT16   | CALCULATES STRESS IN BAR ELEMENT II UNDER<br>LOAD CONDITION JJ                                                                                       |
| SADT17   | PRINTS FORCES OR STRESSES IN BAR ELEMENTS                                                                                                            |
| SADT18   | CALCULATES GRADIENT INFO IN FINITE ELEM<br>STRUCTURAL ANALYSIS                                                                                       |
| SADT19   | ADDS ELEMENT MASS AA OF ELEMENT II<br>TO GLOBAL MASS MATRIX                                                                                          |

SADT20 CALCULATES THE PARTIAL DERIVATIVES OF THE DISPLACEMENTS WRT INDEPENDENT DESIGN VARIABLE II

SADT21 CALCULATES STRESS AND GRADIENT OF STRESS IN BAR ELEM II UNDER LOAD COND JJ GIVEN DISPLACEMENT VECTOR PL AND GRADIENTS OF THE DISPLACEMENTS IN VECTOR DU

SADT22 PERFORMS STRESS-RATIO DESIGN OF A FIXED GEOMETRY TRUSS

SADT23 CALCULATES WEIGHT OF TRUSS GIVEN AREAS AND LENGTHS

SADT26 CALCULATES THE GRADIENT OF WEIGHT WRT RECIPROCAL DESIGN VARIABLES

SADT31 CALCULATES GRADIENT INFORMATION AND STORES IN ARRAY TAY

SADT34 CONMIN EXTERNAL FOR TRUSS FIXED GEOMETRY DESIGN

SADT35 CALCULATES GRADIENT INFORMATION AND STORES IN ARRAY TAY

SADT36 CALCULATES  $(X_{EIG} - T^*AM * X_{EIG})$  FOR GRADIENT CALCULATIONS IN FREQUENCY CONSTRAINTS

SADT37 CALCULATES EIGENVALUE GRADIENT INFORMATION IN FINITE ELEMENT STRUCTURAL ANALYSIS AND DESIGN

SADT40 CALCULATES GRADIENTS OF DISPLACEMENTS WRT COORDINATE DESIGN VARIABLE II

SADT41 CALCULATES GRADIENT INFORMATION WRT COORDINATE VARIABLES

SADT42 CALCULATES GRADIENT OF WEIGHT WRT COORDINATE DESIGN VARIABLES

SADT43 CALCULATES GRADIENTS OF OBJECTIVE AND ACTIVE CONSTRAINTS IN OPTIMUM GEOMETRY DIRECTION FINDING PROBLEM

SADT44 PERFORMS TRUSS FIXED GEOMETRY DESIGN AND EVALUATES CONSTRAINTS

SADT45 PERFORMS TRUSS OPTIMUM GEOMETRY DESIGN

SADT46 READS INPUT INFORMATION FOR BAR ELEMENTS

SADT48 BUILDS THE ELEMENT MASS MATRIX FOR A TRUSS FINITE ELEMENT

SADT49 SOLVES REAL EIGENVALUE PROBLEMS USING THE SUBSPACE ITERATION METHOD

SADT50 BUILDS INITIAL SET OF BASIS VECTORS FOR EIGENSOLUTION BY REDUCED BASIS METHOD

SADT51 CALCULATES STRESS AND GRADIENT OF STRESS IN BAR ELEMENT II UNDER LOAD CONDITION JJ, GIVEN DISPLACEMENTS CONTAINED IN VECTOR PL AND GRADIENT OF DISPLACEMENTS

IN VECTOR DU

SADT52 PERFORMS 1-DIMENSIONAL SEARCH IN  
COORDINATE DESIGN SPACE

SADT53 PRINTS MEMBER INFORMATION FOR BAR ELEM

SADT54 CALCULATES AND PRINTS CENTER-OF-GRAVITY  
AND INERTIAL PROPERTIES OF FINITE ELEM  
STRUCTURE

SADT61 BUILDS GLOBAL MASS MATRIX

SADT62 PRINTS NEIG EIGENVALUES STORED IN  
EIGVAL, AND THEIR CORRESPONDING  
EIGENVECTORS STORED IN XEIG

SADT71 PRINTS G VECTOR OF CONSTRAINTS

SADT73 CALCULATES GRADIENT INFORMATION

SADT74 PRINTS TAY ARRAY OF GRADIENTS

SADT75 CALCULATES GRADIENT OF WEIGHT WITH  
RESPECT TO AREA DESIGN VARIABLES

SADT76 CALCULATES GRADIENT OF WEIGHT WITH  
RESPECT TO COORDINATE DESIGN VARIABLES

SADT77 CALCULATES GRADIENT INFORMATION

SADT79 PRINTS COORDINATE INFORMATION

MSADT DRIVER PROGRAM FOR USING THE ABOVE  
SUBROUTINES. MSADT MAY BE COUPLED  
TO OPTIMIZER OF USER'S CHOICE.

XMSADT SUBDRIVER PROGRAM FOR COUPLING  
SADT ROUTINES TO MSADT

#### LIST OF REFERENCES

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