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USER MANUAL FOR BUNVIS-RG: AN EXACT BUCKLING AND VIBRATION PROGRAM FOR LATTICE STRUCTURES, WITH REPETITIVE GEOMETRY AND SUBSTRUCTURING OPTIONS

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CONTENTS

1 SUMMARY

A computer program is described which is especially suited for making vibration and buckling calculations for prestressed lattice structures that might be used for space application. Structures having repetitive geometry are treated in a very efficient manner. Detailed instructions for data input are given along with several example problems illustrating the use and capability of the program.

2 INTRODUCTION

BUNVIS-RG (BUckling or Natural VIbration of Space frames with Repetitive Geometry) is a FORTRAN 77 computer program with approximately 11,000 lines of coding, which uses the stiffness matrix method and exact member theory. It finds the eigenvalues, i.e. the critical load factors in buckling problems or the natural frequencies in undamped vibration problems, with the option of finding the corresponding mode shapes. It covers three-dimensional frames consisting of uniform beam-column members and/or taut strings. Special care has been taken to account for rigid body modes and prestressing, so that frames in space can be analyzed. An optional static analysis provides the internal member forces that are needed by the eigenvalue analysis. The eigenvalue results are exact in the sense that the beam-column member equations used were obtained by solving the governing differential equations of Timoshenko theory to allow for the effects of axial force and shear deflections and, additionally in vibration problems, of distributed mass and distributed rotatory inertia. Dramatic computational savings can often be obtained by using the exact repetitive geometry and substructuring features of the program. The former enables structures which are repetitive in any number of coordinate directions, including rotational periodicity, to be treated by solving an eigenvalue problem of the size associated with the repeating portion of the structure.

BUNVIS-RG has been developed from the earlier program BUNVIS (ref. 1), which was not made generally available although it is a well tested research program which was developed at UWIST (The University of Wales Institute of Science and Technology) and has been used for several years both there and at the NASA-Langley Research Center. BUNVIS-RG was principally developed at Langley, with collaboration from UWIST, by adding repetitive geometry and many practical features, such as the preliminary static calculations, automatic node renumbering to reduce bandwidth, a "user friendly" data preparation scheme, plotting, flexible joints, and offset connections at nodes. All such features are treated exactly for eigenvalue problems, whereas conventional finite element programs usually make some approximations unless additional nodes are added.

BUNVIS-RG is available to US users from COSMIC*, and to other users from the second author. The principal aims of this manual are to describe the program's capabilities and to present the user instructions necessary for its application. Example problems are given to illustrate specific input requirements and timing estimates as a function of problem size are developed. To avoid obscuring the primary aim of the manual, the novel aspects of the theory are given in separate publications which are cross-referenced.

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3 MAIN FEATURES OF BUNVIS-RG

BUNVIS-RG uses exact member theory for beams and taut cables which accounts for distributed mass and axial force correctly, and finds selected eigenvalues by using a theoretically established algorithm (refs. 2 - 4) which ensures that none are missed. The algorithm involves a stiffness matrix that is a function of the eigenparameter, i.e. of the frequency or load factor. Gauss elimination is applied to this matrix at a trial value of the eigenparameter to enable the algorithm to determine the number of eigenvalues exceeded, and this is repeated for successive trial values of the eigenparameter. In previous applications these trial values have often been chosen by a bisection routine. However, BUNVIS-RG has a new accelerated convergence routine which uses the determinant of the stiffness matrix and which retains the certainty of the algorithm while being about twice as fast as bisection. The program can account for the effects of axial forces on the flexural vibrations of members, so that natural frequencies can be found for loaded structures. The axial forces can be given as data, or can be found from preliminary static calculations which include the combined effects of external loads applied at the nodes (i.e. joints), acceleration such as gravity and axial member preloads or prestrains. BUNVIS-RG can allow for: any topology of a three-dimensional frame; rotatory inertia and shear deflection of members; unequal principal second moments of area of cross-sections of members with arbitrary alignment of principal axes; generally tapered members with varying axial load; elastic connections between members and nodes; offset connections between members and nodes; cylindrical or Cartesian coordinates; and nodes which have lumped masses and/or lumped rotatory inertias and/or elastic or rigid supports. In addition, BUNVIS-RG can: find buckling or vibration mode shapes; plot such mode shapes and the undeflected shape of the frame; give greatly reduced solution times for structures which are linearly and/or rotationally repetitive; include members with any combination of stepped and smoothly varying properties by a general substructuring capability; and include stayed columns in a frame by using a special purpose but very efficient substructuring capability. The remainder of this section gives details and references where needed to define the theoretical aspects of the above features. An important contrast with finite element programs is that exactness is retained by all these features (except for the general tapered route where the member is approximated by a user selected number of uniform elements to generate a set of substructure stiffnesses for the complete member). There is no need to introduce extra nodes or members even for the highest eigenvalues because the member theory retains the infinite number of degrees of freedom, and hence of eigenvalues, of the real structure.

3.1 Member Theory

The member equations used are the classically exact ones obtained by solving the appropriate differential equations. The stiffness coefficients which result are functions of the axial force in the member, and are also functions of frequency in vibration problems. The expressions used for the stiffness coefficients of a taut string are those given in reference 5. The remaining stiffness coefficients are essentially those given in references 6 and 7 for vibrations of an axially loaded Timoshenko beam. These have the data triggered option of omitting any combination of frequency, axial force, rotatory inertia and shear deflection. Thus static and Bernoulli-Euler stiffnesses are included.

3.2 Convergence on Eigenvalues

BUNVIS-RG can find: a set of data-specified eigenvalues, such as the first and the third, where the first is the fundamental; all eigenvalues between specified values of the eigenparameter, e.g. to find all the natural frequencies in a frequency band; or the number of eigenvalues (and hence the modal density) in each of the equal intervals between evenly spaced values of the eigenparameter. The options all use the theoretically proven algorithm described above, that guarantees successful convergence on all the required natural frequencies of (dead) loaded structures (ref. 2), or on the critical load factors of structures subjected to a dead (i.e. constant) load system and to a live load system which is scaled by the load factor (i.e. proportional loading) (ref. 3). The simplest route in BUNVIS-RG assumes that the dead or live load systems can be approximated adequately by the axial forces which they cause in the members, and that these axial forces are known a priori and constitute the dead and live load data. The alternative routes involve the static calculations described in section 3.3.

3.3 Static Loading, Including Prestress and Acceleration

For buckling and vibration problems, BUNVIS-RG can calculate the dead load axial forces caused in the members by any combination of externally applied static point forces and moments at the nodes, axial preload or prestrain in the members, and acceleration loads such as those due to gravity. This is done by replacing the preloads, prestrains and acceleration forces by equivalent static point forces at the nodes, adding these to the externally applied forces at the nodes, and then solving by the usual static stiffness matrix method. The live load axial forces can be found similarly, except that acceleration is not included.

Such preload and prestrain calculations in effect assume that the structure is assembled with the preloads and prestrains in its members given by data and its nodes clamped, and that the nodes are then released to distribute the prestress through the structure. Gravity, or any other acceleration loading of a structure, is accounted for by sharing the mass of each member or substructure according to its center of gravity location between the nodes at its ends and converting to forces by using the appropriate acceleration. The acceleration is specified by giving its components in the three principal coordinate directions so that acceleration in any direction can be treated.

The static stiffness matrix is a function of the initial axial forces in the members, which are supplied as data. When dead load and live load axial forces are given in data they are added together with the latter scaled by the initial load factor. Hence the most accurate results are obtained when these axial forces are close approximations to the final axial forces in the members.

The static loading calculations should alter the dead and live load axial forces in members within a stayed column substructure from those given in data, but at present this calculation is not performed. (However, the end load on the stayed column is calculated and could be used to find the axial forces in its members, e.g. by a separate BUNVIS-RG run.)

3.4 Dead Load and Rigid Body Modes

It is meaningless to find natural frequencies of a buckled structure using linear theory, and similarly the algorithm used (ref. 3) to find critical buckling loads of structures subjected to dead and live loading presupposes that the structure is stable when the dead load is applied alone. Therefore, for both vibration and buckling problems, a preliminary calculation is performed which uses the algorithms of references 2 and 3 to check that the structure is stable under the dead load alone. This check can fail when rigid body freedoms exist, unless precautions are taken. Therefore, BUNVIS-RG allows a single data-specified small stiffness (SMASPR) to be added (after appropriate scaling, see section 4.6.4) to all three translational freedoms at every node of the structure. Suitable choice of this stiffness leaves the eigenvalues essentially unaltered, while replacing the rigid body modes by very low eigenvalues which need not be computed. However, the presence of even quite small implied external loads at the nodes must then be avoided because they could make this structure unstable. Such loads would result if the dead load axial forces are not close enough to being in equilibrium at the nodes. This happens if the axial forces used are those given in data, and the forces and/or geometry are not given to high accuracy. It would also usually happen if the axial forces are calculated by the program (see section 3.3) because such calculations include the shear forces, so that the axial forces alone will not usually be in equilibrium at the nodes.

To avoid this static instability problem, the program has three options which may be employed for structures that have rigid body degrees of freedom. The choice depends on the type of structure. For a structure that is redundant, and is not a mechanism when modeled as a pin connected truss, the static analysis may be performed on this basis to yield axial forces that are in equilibrium. If the user is satisfied that these forces differ very little from those found using the full member stiffnesses, the error in the subsequent eigenvalue calculation based on the full member stiffnesses should be small. If this approach is not suitable but shear forces from the stress analysis are reasonably small, an alternative approach is to specify a small quantity (PDELTA) in the input which increases all tension loads and decreases all compression loads by PDELTA times their correct values. If a value of PDELTA can be found that will result in a net tension across the structure, no instability will occur. The error in any eigenvalue calculated this way when expressed as a ratio to the correct eigenvalue is usually less than PDELTA. For some structures, large shear forces are required to provide equilibrium and neither of these approaches would work. For this case, the program has the option of adding the effect of static member shear force to its usual member equations (refs. 6, 7), which already allow for the static axial force. To do this, the terms $\pm Q/L$ are added in appropriate locations of the member stiffness matrix, where Q is the static shear force and L is the length of the member. For buckling problems, Q includes the live load scaled by the current value of the load factor. The theoretical basis of the additions to the stiffness matrix can be deduced by fairly simple arguments, or can be deduced more rigorously from reference 8. This approach is an approximation which does not remove the static instability in all cases and should be used with caution. Since internal loads of stayed column substructures are not recovered from the stress analysis to be used in subsequent eigenvalue analysis, a similar correction is made involving the change in axial load that was determined from the stress analysis.

3.5 Mode Finding

Modes are found by a random force vector method. This method is the "P_{RT} method" which was advocated and evaluated in reference 9. Briefly stated, it consists of solving the equations (stiffness matrix of the structure) x (displacement vector) = (force vector), with the elements of the force vector given random values and with the stiffness matrix evaluated at a close approximation to the eigenvalue. When mode shapes are calculated for several coincident eigenvalues, the program finds a mode for each by the expedient of using a different random force vector in each case.

3.6 Use of Core Storage and Resequencing of Nodes

BUNVIS-RG is an in-core program (except for data handling, plotting and, optionally, for the static loading calculations of section 3.3 and mode finding) which was written to keep the amount of coding and the core store requirement (for data and working space combined) as small as was reasonably possible while also keeping execution time near optimum. Thus it employs a fixed bandwidth method which only stores the active triangle of the band during assembly and Gauss elimination, as described in connection with figure 2 of reference 10. This results in low working space requirements, but if modes are required, the entire upper half band of the stiffness matrix must be stored. The user has the option of doing this in core or with the use of backing store depending on problem size and storage available. Virtually all the array space needed is contained by three one-dimensional arrays, which store the integer, real and complex numbers of the data and working space without gaps. Working space is minimized by re-using it whenever possible.

Because solution time and storage are bandwidth dependent, BUNVIS-RG incorporates the program BANDIT (ref. 11) to give the option of reducing the bandwidth. The BANDIT program uses both the Cuthill-McKee (ref. 12) method and the Gibbs-Poole-Stockmeyer (ref. 13) method. The four options for resequencing contained in the original BANDIT program are retained and are:

option	criterion
1	rms wavefront
2	bandwidth
3	profile
4	max wavefront

Option 2, reduction of bandwidth, is usually the best suited for BUNVIS-RG and is the default value in the program. For discussion of the other options see references 11-13. For many problems the minimum bandwidth is achieved by BANDIT, but the method does not always result in a minimum when the topology is complicated.

3.7 Stayed Columns

An important feature of BUNVIS-RG, which accounts for about 250 lines of coding, is the inclusion of a very efficient (i.e. low store requirement and fast execution), exact, substitute* column method (ref. 14) for handling stayed columns as substructures. These stayed columns are symmetric about their mid-length and consist of a central core with N=3,4,5..... identical stay frames equally spaced round it as shown in figure 1(b). The stay frames can consist of any combination of beam-columns and taut strings (i.e. stays) which lie in a plane, but stay frames are not inter-connected except where they are connected to the core. Thus figure 1(a) shows a typical stayed column, which can be represented in data merely by the representative half frame of figure 1(c). An example of the efficiency of this substructure approach was given in reference 15 where a frame with almost 22000 degrees of freedom (considering all the nodes in the stayed column substructures) was treated in a modest amount of computer time.

3.8 Repetitive Geometry

Frames which contain a group of nodes and members which repeats in one or more coordinate directions may be analyzed using the repetitive feature of the program. The size of the problem analyzed is only that corresponding to the repeating portion of the frame but results are applicable to the complete frame. Figures 2 and 3 illustrate large repetitive structures that have been analyzed by using this repetitive geometry feature. In general BUNVIS-RG handles linear repetition in any combination of one, two (see figure 2) or three Cartesian directions, and also handles rotational periodicity (see figure 3) with the option of linear repetition in the direction of the axis of rotation.

The detail of the repetitive geometry method is given in full in reference 16 with the theory in the appendix for a central node replaced by the alternative and more general approach of reference 17. Briefly, this method requires that the response mode be repetitive over a certain number of bays in each coordinate direction as given by equation (2) of reference 16 as

$$D_j = D_0 \exp[2i\pi(n_1 j_1/N_1 + n_2 j_2/N_2 + n_3 j_3/N_3)] \qquad (1)$$

where D_j is the displacement vector in the j^{th} repeating portion located j_k bays in each coordinate direction from the structure actually modeled. The mode repeats in each coordinate direction in N_k bays for k = 1, 2, 3. The n_k are harmonics of response which must cover the range

$$n_k = 0, \pm 1, \pm 2, \ldots, \pm \mathrm{integer}(N_k/2) \qquad (2)$$

to ensure that all possible independent responses are accounted for. For structures repetitive in only one direction, negative values of n_k need not be

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* Reference 14 gives several variants of the substitute column method. The one used in BUNVIS-RG is particularly efficient, being that described around figure 3 of reference 14, in the form in which three degrees of freedom are allocated to every node and are chosen to permit whichever of in-plane or out-of-plane deflections of each stay frame of the types I, II_a or II_b substitute columns is required by the theory.

considered. For structures repetitive in two or three directions, negative values of n_k need not be considered for one direction, but both positive and negative values must be used for the remaining directions. A more complete discussion of these requirements is given in reference 16.

Introduction of equation (1) results in complex quantities which are eventually incorporated into the stiffness matrix in the analysis. The program uses the complex arithmetic feature of Fortran to implement the solution. For nonrepetitive structures, the stiffness matrix is real. To account for this, it is possible to compile two versions of the program, a real arithmetic version for regular problems and repetitive problems with a harmonic response of 0, or $N_k/2$ when N_k is even, and a complex arithmetic version for general repetitive problems. The complex version will work the regular problem but with a factor of approximately three to five penalty in time depending on the machine and compiler used. The only difference between the two versions is one line of code declaring certain variables to be complex which is omitted in the real version. This line is identified with a comment card in the source code.

The program is particularly useful for structures having rotational periodicity, where the mode inevitably repeats in the circumferential direction. Alternatively, for structures of finite size which are repetitive in rectangular coordinates and which have simply supported boundaries and appropriate symmetry in geometry and loading, solutions can be obtained by assuming a mode that is repetitive over twice the length of the actual structure. Moreover, even if symmetry and boundary condition requirements are not satisfied so that the assumed mode shape will not be compatible with the actual supports, the results for wavelengths that are small relative to the length of the structure may still help the analyst.

It is apparent from the number of nodes for the full structures of figures 2 and 3 compared with the number of nodes for their repeating portions, that computer time and storage savings must be very great for the analysis of these structures using the repetitive feature of the program. The repetitive geometry method gives exact results for rotationally periodic structures. It also gives exact results for the spatially sinusoidal response of linearly repetitive structures. Such results will be exact for structures with boundary conditions which are compatible with a suitably chosen set of sinusoidal responses and otherwise can give useful approximations. The inclusion of rotationally periodic space frames with members along their axis of periodicity needed an extension of the original algorithm for ensuring convergence on all required eigenvalues, which reference 17 shows is valid for any rotationally periodic structure.

3.9 Elastic and Offset Connections Between Members and Nodes

By default, the program assumes that the center-lines of members pass through any node to which they are connected and that all six degrees of freedom (three translations and three rotations) are rigidly connected to the node. Alternatively, any combination of the six freedoms (in member co-ordinates) at each end of a member can be elastically connected to the node. Reference 18 gives details of the simple and efficient way in which these elastic connections are introduced one at a time so as to retain the exactness of the results and the certainty of the algorithm which ensures that no eigenvalues are missed. Zero elastic stiffnesses can be used to obtain pinned or sliding connections. Offsets, i.e. eccentric connections between a member and a node, can also be applied, using a standard transformation, in any combination of the three Cartesian global axis directions. Alternatively, the offsets can be defined using a local set of member axes. Note that when elastic connections and offsets are both present the former are applied to the member first. Thus, if the offsets are visualized as rigid links between the ends of the members and the nodes, the elastic connections are between the members and the rigid links, which are always rigidly connected to the nodes.

3.10 Tapered, Stepped, or Non-Uniform Members

BUNVIS-RG includes exact Bernoulli-Euler theory member equations for tapered members which have taper such that their axial and flexural rigidities vary according to, respectively,

$$EA = EA_o(1 + c\frac{z}{L})^n \quad \text{and} \quad EI = EI_o(1 + c\frac{z}{L})^{n+2} \qquad (3)$$

with $n = 1$ or 2, and $c > -1$, where z is measured from one end of a member of length L. The mass per unit length varies as EA and the twisting stiffness and polar moment of inertia vary as EI. The expressions used for the individual member stiffnesses are explicit ones which involve Bessel functions. They only cover either vibration of members which do not carry axial load (ref. 19) or static behavior of axially loaded members (ref. 20). Thus they can be used for vibrating frames in which the tapered members are unloaded, or for buckling of frames.

BUNVIS-RG also includes a substructuring route which automatically generates a stepped beam which can represent a non-uniform member as any required number of rigidly jointed uniform members. These uniform members are analyzed by the Timoshenko beam-column theory described earlier in this manual, and their principal properties can be varied independently of each other between successive uniform members to follow profiles along the length of the non-uniform member which are given in data as algebraic curves. The data required by the program is very concise, and an extra data input refinement makes it even more so for profiles which satisfy equation (3). Thus tapered members which satisfy equation (3), but do not satisfy the requirements stated in the paragraph which contains it (e.g. the beam is an axially loaded vibrating one, $n > 2$, or Timoshenko theory is needed), require only a minimum of input data.

The substructuring facility also allows any number of uniform Timoshenko beam-columns and/or any combination of tapered or non-uniform members of the kinds already described in this sub-section, to be rigidly or elastically (but not eccentrically) connected in a straight line to form any tapered, stepped or generally non-uniform beam-column for which flexure in the two principal planes, axial response, and torsional response are all uncoupled. Such uncoupling is also assumed throughout the analysis described earlier in this section, so that all substructuring uses minimum bandwidth substructure stiffness matrices by considering separately in-plane flexure in each of the two principal planes, axial behaviour and torsional behavior.

3.11 Estimating Solution Times

The solution time to find eigenvalues without modes, T, is the product of the number of iterations taken by the convergence routine, I, and the time taken per iteration, T_i. Thus

$$T = I \times T_i \tag{4}$$

A stress analysis takes one iteration plus the time required for back substitution to determine the deflections from which the internal forces are determined. For eigenvalue analysis, the value of I depends on the problem and can only be estimated from experience. Thus I typically depends upon the number of eigenvalues sought, the accuracy to which they are required, and whether they occur in clusters of close or coincident values. As a rough guide, the accuracy required for reasonably accurate mode shapes is .001%. For this accuracy, I will receive a contribution of about eight for each well separated eigenvalue where the accelerated convergence procedure is used, and a contribution of about sixteen for each group of coincident eigenvalues where bisection must be used. For each mode shape calculated in-core, I will receive an additional contribution of between 1 and 2. However the accuracy of a mode is frequently much less than that of its eigenvalue, so that extra iterations may be needed to improve the accuracy of the mode by finding the eigenvalue more accurately.

A fixed bandwidth method is used to perform the Gauss elimination, which can therefore be assumed to take a time which is proportional to $B^2(N - \frac{2}{3}B)$ where N is the number of nodes and B is the bandwidth defined as one greater than the maximum node number difference of any pair of connected nodes. The Gauss elimination time dominates T_i when B is large, but the calculation of member stiffnesses and their transformation to global axes can also be significant if B is small. Therefore for frames with uniform beam-column members (and without stayed columns or tapered, stepped or non-uniform members) T_i can be estimated from

$$T_i = \alpha B^2(N - \frac{2}{3}B) + \beta M \tag{5}$$

where M is the number of uniform beam-column members in the frame and α and β are dependent on the machine and compiler used and upon whether the real or complex program is used. A number of runs (described in more detail in reference 21) on structures having a wide range of B, M, and N resulted in the following values for α and β

	Real		Complex	
Computer	α	β	α	β
VAX-11/780 (UWIST)	0.00164	0.0145	0.00843	0.0157
VAX-11/780 (NASA)	0.00251	0.0181	0.00951	0.0194
CDC-CYBER 855	0.000191	0.00337	0.000450	0.00345

An estimate of the time required for an iteration is calculated from equation (5) and printed for each run. Note that the VAX times are different for the two installations. Users may wish to develop their own values of α and β based on their own experience and change the values that are given in the source code. The value of β is increased by the presence of tapered or stepped members and decreased for members having equal rigidities, members aligned with principal axes, members connected to earth nodes, and members in a plane frame. For further details on timing, see reference 21.

4 INPUT DATA PREPARATION

Some of the more significant features of BUNVIS-RG which a user should be aware of in preparing input are summarized in the following list.

- Rectangular and cylindrical coordinates
- Stress analysis for external loads with automatic inclusion of acceleration and gravity loadings
- Preloaded or prestrained members such as due to temperature can be included in the stress analysis
- Repetitive geometry
- Members having unequal principal moments of inertia
- Tapered and stepped members
- Members offset from nodes
- Members having spring connections to nodes including pinned or sliding connections
- Stayed column substructures
- Plotting of undeformed structure and mode shapes

This section presents general aspects of the required modeling followed by a detailed description of the input. Groups of numerical data are generally preceded by a descriptive heading card. Only the first two or three letters of these cards are usually required by the program; the actual letters required are indicated in the following text by capitals.

4.1 Coordinate Systems

The global axes form a right hand system which may be rectangular (x, y, z) or cylindrical (r, θ, z). The integers 1, 2 and 3 are used respectively to indicate forces or displacements along these axes for several input quantities and similarly 4, 5 and 6 are used to indicate moments or rotations about these axes. The sign convention for moments or rotations follows the usual right hand rule. The local member coordinate system is a right hand rectangular one oriented with respect to the global system as shown in figure 4. The positive z axis is along the member in the direction from the lower numbered node (initial end) to the higher numbered node (final end). The local x and y axes are defined as indicated in figure 4 with a complete explanation of the rules given in the definition of CT in the SECtion data card group. Default values are such that the local x axis lies in a plane normal to the global z axis.

4.2 Stress Analysis

A stress analysis may be made in order to calculate the individual member axial forces to be used in the subsequent buckling or vibration analysis. The stress analysis includes the combined effects of external loading at any node (point forces and moments and the automatic inclusion of acceleration or gravity loads at nodes if desired) and members having preloads or prestrains such as due to temperature. The stiffness matrix used in the stress analysis may include the effect of member axial force, see section 3.3. The results of the stress analysis are the axial and shear forces and bending and twisting moments at the ends of each member. In subsequent eigenvalue analyses, the member axial force is accounted for directly in the member stiffness matrix except for stayed column substructures. The effect of member axial force for stayed column substructures and the effect of shear forces can be approximated in the eigenvalue analysis as described in section 3.4. These effects may be switched on by setting IQL = 1 after a RESet card. For tapered or stepped substructures that appear in more than one location, only one substructure stiffness matrix is used which is determined from the axial load for the first occurrence of the substructure. If the structure is repetitive, the loadings are the same in all repeating elements (i.e. they correspond to the zeroth harmonic) no matter what harmonics are used in the subsequent eigenvalue analysis.

4.3 Modeling Repetitive Structures

A structure that has repetitive geometry can often be analyzed at greatly reduced time and cost in BUNVIS-RG if the repetitive feature of the program is utilized. The capabilities and limitations of such an analysis are discussed in section 3.8. The first step in preparing data for a repetitive structure is to identify the repeating portion, which contains a group of nodes and members which repeats in one or more coordinate directions. This group of nodes and members is defined as the basic repeating portion. Every node in each repeating portion is given the same number as its counterpart in the basic repeating portion. The difference in coordinates of a node and its counterpart in the next repeating portion is the bay width in that direction and is input in the BAY information group as the quantity ZJ(I), where I = 1, 2 or 3 corresponding to the three global axes. The number of bays over which the mode shape repeats must be given in the same card group as EN(I). The desired response harmonics as discussed in section 3.8 are specified in the MODe card group. The nodes may be numbered in any order keeping in mind that efficiency is increased by minimizing bandwidth. The nodes may be resequenced to reduce bandwidth by the input of the BANdwidth card. The basic repeating portion is modeled just as for a nonrepetitive structure with the additional requirement that the lower numbered of the two nodes connected by a member (or substructure) must be in the basic repeating portion, whereas the higher numbered node can be in the basic repeating portion, or can be in any other repeating portion. (In which case this node number can duplicate the lower numbered node to permit a node in the basic repeating portion to be connected to its counterpart in any other repeating portion.)

4.4 Modeling Stayed Column Substructures

Stayed columns that are symmetric about their mid-length and have a central core with N = 3, 4, 5, ... identical stay frames equally spaced around the core are treated with the same exactness that is in the basic program using the theory of reference 14. The stay frames can consist of any combination of beam-columns and taut cables which lie in a plane but are not inter-connected except through the core member. The core and stay frames terminate at a single node at each end. The stayed columns are modeled separately as substructures which can then be incorporated into the final structure by connection of the two end nodes. If a stress analysis is made, the axial load on any stayed columns in the structure is determined, but the forces on individual members making up the stayed column are not. In a subsequent eigenvalue analysis, the effect of the end forces may be included as discussed in section 3.4 to retain equilibrium at a node. The mode shape in the interior of a stayed column is also not recovered but an interpolated shape based on end point deflections and rotations is plotted.

4.5 Modeling Tapered and Stepped Members

There are several options for modeling nonuniform members as either continuous tapered members, stepped members, or a combination as discussed in section 3.10. In all cases the member is treated in the program as a two-noded substructure whose stiffnesses are calculated at the beginning of each iteration for all such members. It may be advantageous to treat a uniform member by this approach if it appears many times in the structure at the same length to avoid recalculation of the stiffnesses which would be done if treated in the regular way. Members whose properties vary according to equation (3) can be modeled using just the TAPer group. More general tapers require the addition of the VARiation and PROfile groups. A general two-noded substructure can be generated by linking any number and combination of uniform and tapered members together in the STEpped card group.

4.6 Data Input

The input is free field with the following general features:

(1) Numerical data may be separated by blanks or commas.

(2) Trailing zeros on lines of data having a specified number of entries need not be entered.

(3) Comments may be inserted on any card after inserting a $. Data may be resumed on the same card after a second $.

(4) A capability for generating data that repeats in a regular pattern, such as coordinates or connectivities, is available and described in section 4.6.5.

The input data is separated into several groups that are each identified by a descriptive heading that precedes the numerical data. These groups may appear in any order. Only the first three letters of each heading (unless otherwise indicated) are used by the program so that the remaining characters are only used as a prompt to the user. The necessary letters for each name are identified with capital letters in this manual. Each card group containing numerical data that may appear in a run is identified in the following with an * preceding the heading card; each card group that is always required in any run is identified with ** preceding the heading card. Specific examples of most of the data input are given in the example problems listed in tables 1 to 8.

For a given problem, the data in many of the groups is not applicable and those groups may be omitted. Because of default values contained in the program certain other groups may not be required. The minimum number required are the MEMber data, SECtion properties, CONnection list, and COOrdinates. If any of these groups is missing after all input has been read, the program prints a warning message and stops. In the following, the various headings are listed in the order that they appear in the output along with a description of the data that is entered.

4.6.1 Analysis Control The following cards control input, output, and the analysis options available to the user.

ECHo on	Input data after this card will be printed in the output exactly as entered and will also be printed in an organized listing with descriptive headings. Default is ECHo on.
ECHo OFF NOEcho	Either card turns off printing of input data subsequent to where the card is inserted, including the organized listing.
EXPlanation	Causes explanatory headings to be printed at the beginning of major tables of data appearing in output.
INTeger	Coordinates given as integers that refer to the list of REAl numbers. Without the INTeger card, coordinates are given directly their real values under the COOrdinate heading.
DEGree	Angles given in degrees for cylindrical coordinates. Without the DEGree card, angles for cylindrical coordinates must be given in radians.
PLAne frame	Analysis is performed for a plane frame.
STRess	Causes stress analysis to be made. If the STRess card is present with either a BUCkling or VIBration card, internal member loads will be determined from the stress analysis before the buckling or vibration analysis is performed.
BUCkling VIBration	Causes buckling or vibration analysis to be made. It is not possible to execute a buckling and a vibration analysis on the same run.

* CRIteria (One card containing 4 items of data)

Item

1	CF	Convergence factor. Eigenvalues are obtained to an accuracy of at least 1 part in CF. Default is 1.E5.
2	FQ	Defines a positive trial value of first required eigenvalue or the lower bound on range of eigenvalues or eigennumbers depending on the value of NDIV. Default 1.
3	FP	A non-zero absolute value of FP gives the upper bound on a range of required eigenvalues or eigennumbers depending on the value of NDIV. If FP is negative, modes will be found for each eigenvalue found, with the exception that only one mode is found for a group of coincident eigenvalues. Default 0.
4	NDIV	If NDIV is zero, all eigenvalues from eigennumber FQ to eigennumber FP are found. However, if FP is also zero, the list

of required eigennumbers is given by the EIGenvalues card group. If NDIV is negative, all eigenvalues in the range FQ to FP are found. If NDIV is positive, the range FQ to FP is divided into NDIV equal parts. No eigenvalues are found, but at each point of division, the number of eigenvalues exceeded is determined, and modal densities are listed. Default 0.

The following examples illustrate the various options.

1.E6 2.

This CRIteria card will cause all eigenvalues listed in the EIGenvalues card group to be found with an accuracy of one part in one million starting with a trial value of 2.

1.E4 5. 20. -1

This CRIteria card will cause all eigenvalues in the range 5. to 20. to be found.

1.E5 20 35 0

This CRIteria card will cause eigenvalues numbered 20 to 35 to be found.

1. 2. 100. 98

This CRIteria card will cause modal densities to be found in the range 2. to 100. at intervals of 1.

* EIGenvalues (Any number of cards containing integer data.)

List of required eigenvalue numbers. Used only if FP and NDIV are zero on CRIteria card. A negative sign will cause a mode shape to be calculated for that particular eigenvalue. If no input is given in this group a default value of -1 will cause the first eigenvalue to be obtained along with the mode shape.

BANdwidth optimization N

BAN ... N causes the node reference numbers to be resequenced to reduce solution time, using option number N of the BANDIT program. If N is omitted the recommended default value of 2 is used. For other options see section 3.6.

SHOw resequence

Input data that has changed as a result of renumbering and resequencing is printed with reference numbers that are used internally in the program.

<u>4.6.2 Structural Description</u> The following groups of cards are used to describe the structure and its loading. In many cases, reference numbers are used, such as for nodes, SECtion properties, tables of REPetitive members or SPRing connections and other similar data. In all cases these numbers may be arbitrary and given in any order.

* SET (One card containing 4 items of integer data.)

Item

1	ICORD	Set to 1 for rectangular coordinates; 2 for cylindrical coordinates. Default 1.
2	LC	Set to 0 for regular problems. A value of 1 causes all rotational degrees of freedom of nodes to be restrained which would be necessary for a structure having only pin ended and cable members. Default 0.
3	LR	Use 1 if rotatory inertia of the members is to be allowed for in a vibration problem, otherwise use 0. Default 0.
4	LS	Use 1 if shear deflection of the members is to be allowed for, otherwise use 0. Default 0.

* REAl number list (Any number of cards and items of data.)

A series of real numbers that may be referenced to define coordinates, lumped masses and inertias, and spring stiffnesses.

** COOrdinates (Any number of cards containing data in groups of four.)
SUB N

The second heading card is optional for the final structure where N is zero. For stayed column substructures, N is the substructure reference number. The first item in each group of four is the node reference number followed by the three coordinates (x, y, z or r, θ, z) of the node. For cylindrical coordinates, θ may be given in degrees or radians according to the presence or absence of a DEGree card.

If the INTeger card is present, the coordinates are given as integers whose absolute values refer to the location of the coordinate value in the list of REAl numbers. A negative integer reverses the sign on the coordinate value used.

Complete restraint of a group of nodes may be obtained by giving their coordinates last. The coordinates of the grounded nodes should be preceded by a card with the heading EARth or GROund. Alternatively, the number of nodes having complete restraint may be specified by NE using the RESet facility.

The rules for the coordinates of a stayed column substructure are similar to those of the final structure with the following additions, noting that the only stayed columns permitted are those which are symmetric about their mid-length.

(1) Coordinates are cylindrical with the origin at the end and z along the core toward the center of the stayed column. Only one half (lengthwise) of a stayed column is defined in terms of the r-z coordinates of one stay frame which must lie in a plane θ = 0.

(2) All nodes on the plane of symmetry which bisects the length of the column must be given first in the order of decreasing distance from the core.
(3) There must be at least two nodes on the plane of symmetry.
(4) The highest node number must correspond to the end which is attached to a node in the final structure.
(5) The nodes of stayed column substructures are not resequenced when the BANdwidth card is present.

** CONNection list (Any number of cards containing integers that are given as
SUB N triplets.)

The same comments apply to the SUB N card as for the COOrdinate list. The numerical data following the heading card(s) is the connection list, given as triplets of integers. The first two integers of each triplet define the nodes connected, and the last integer is the reference number of the connecting member as defined in the MEMber data group. It is desirable to give the lower numbered node first in a triplet and order the triplets in ascending order of lower numbered nodes. If not entered in this order the data will be rearranged to this order prior to any analysis. If a member connects between the basic repeating portion of a repetitive structure and some other repeating portion, the lower numbered node must be in the basic repeating portion.

* DOF (degrees of freedom) restrained (Any number of cards containing
SUB N integers that are given as triplets.)

Used to apply rigid or elastic constraints at specified degrees of freedom and in vibration problems used to apply concentrated masses and inertias.

The first integer of each triplet is a node number. The second integer corresponds to a degree of freedom in the global coordinate system defined in section 4.1. (A zero indicates all three translational freedoms.) A zero value for the third integer will give complete constraint. A positive value for the third integer will place a mass or inertia taken from the corresponding location in the list of REA1 numbers, and a negative value will place an elastic support, with its stiffness obtained from the list of REA1 numbers corresponding to the absolute value of the third integer. For example, the following data card

1 0 0 3 5 0 7 0 6 10 3 -12

will cause (1) all displacement degrees of freedom at node 1 to be zero, (2) rotation about the y or θ axis (degree of freedom 5) to be zero at node 3, (3) a mass with a value given by the 6th REA1 number to be placed at node 7, and (4) the z displacement at node 10 to be restrained by a spring with stiffness given by the 12th REA1 number.

The SUB N has the same meaning as in the COOrdinate list but, for stayed column substructures, the program is restricted to the input of concentrated masses by the DOF card group.

* STAy frames (Any number of cards and items of integer data.)

Specifies the number of stay frames in each stayed column substructure in the order of ascending substructure reference numbers.

** MEMber data (Any number of cards each containing 7 items of integer data.)

Used to describe the characteristics of each member. Each integer after the member number refers to the reference number of the indicated card group.

Item		
1		Member number
2	SEC	SECtion reference number
3	PRE	PREload or PREstrain reference number
4	REP	REPetition reference number
5	OFF	OFFset reference number
6	SPR	SPRing connection reference number
7	SUB	SUBstructure reference number (i.e. of a stayed column, tapered or stepped substructure). If SUB is nonzero, then SEC and PRE must be zero but any of the other entries may have nonzero values. A card with SUB nonzero is required for every substructure which appears in the connection list, in addition to the card(s) used to define section properties etc. for the substructure or its components.

In the previous data, a zero indicates the absence of a particular quantity for that member.

** SECtion properties (Any number of cards, each containing 10 items of data.)

Item		
1		Section reference number
2	EA	Axial stiffness
3	EIY	Flexural rigidity about the local y axis
4	GJ	Torsional stiffness
5	M	Mass per unit length
6	IP	Polar moment of inertia
7	EIX	Flexural rigidity about the local x axis

8	CT	Used to orient local member x and y axes as indicated in figure 4. If input less than one, CT is the cosine of the angle between the local x axis and the global z axis. If local z and global z coincide, CT is the cosine of the angle between the local x axis and the global y axis. The algebraic sign of CT is determined by requiring that the local y axis always form an acute angle with global z in the first case or global y in the second case. For cylindrical coordinates the above rules also apply with global y replaced by global θ. If CT is an integer equal to or greater than one, the local x axis lies in a plane containing both the line between the nodes the member connects and the node CT.
9	SFX	Shape factor for loads acting in local x direction, i.e. for flexure associated with EIY.
10	SFY	Shape factor for loads acting in local y direction.

Initially all items default to zero but it is essential that a nonzero value of EA be input.

If EIY is zero, the member is a cable which must have tension for vibration problems but may be unloaded for buckling problems.

If EIX is zero, EIX = EIY

If IP is zero, $IP = \frac{M(EIX + EIY)}{EA}$

If SFX (SFY) is zero, SFX (SFY) = SF (See RESet card group for definition of SF). Note that SFX and SFY are used only if LS = 1 under the SET card.

* PREstrains or PREloads (Any number of cards, each with 3 items of data.)

Item

1		Reference number.
2	PD	Value of dead load prestrain or force (positive for tension). If reference number is positive a strain value is input. For thermal stress problems the input would be the thermal strain, $\alpha\Delta T$. If reference number is negative, member axial load is input.
3	PL	Same as PD except for live loads.

* REPetition (Any number of cards, each with 4 integers. Needed only when repetitive feature is used.)

The first number on each card is the reference number and the next three integers indicate the number of bays in the three coordinate directions that the final end of the member is displaced from its initial end corresponding to j_k in equation (1).

* BAY information (One card with 6 items of data. Needed only when repetitive feature is used.)

ZJ(1), ZJ(2), ZJ(3), EN(1), EN(2), EN(3)

The ZJ(K) are the differences in the K^{th} coordinates between adjacent repeating portions. The EN(K) are three numbers giving the number of repeating portions in the three coordinate directions over which the mode is repetitive corresponding to the N_k in equation (1).

For cylindrical coordinates, ZJ(2) is given as an integer (normally EN(2) for a frame that extends around the complete circumference) and the actual ZJ(2) is calculated as:

$$ZJ(2) = \frac{2\pi}{ZJ(2)}$$

* MODes (One card with 6 integers. Needed only when the repetitive feature is used.)

NL1, NU1, NL2, NU2, NL3, NU3

Integers defining lower and upper bounds of the harmonic response n_k in the three coordinate directions. See equation (1).

* OFFsets of members (Any number of cards, each with 8 items of data.)

Item		
1		Reference number.
2	JCORD	A value of 1 indicates that the offsets of the member end from the node are given in a right hand rectangular coordinate system that is aligned with the global coordinate system. A value of 2 indicates the local system defined in section 4.1 is used where the z axis is along the line connecting the nodes.
3 to 5	E1(K)	Offset in the k^{th} coordinate direction of initial end of a member.
6 to 8	E2(K)	Similar to E1(K) but for final end of a member.

* SPRing connections (Any number of cards, each with 13 integers.)

The first integer on each card is the reference number and the next twelve indicate the presence of spring connections corresponding to the twelve degrees of freedom of the member in the x, y, z local coordinate system. The first six integers refer to degrees of freedom at the initial end as defined in section 4.1 with the last six applying to the final end. A zero indicates a rigid connection, a nonzero integer J indicates a spring having a stiffness taken from the J^{th} entry in the list of REAl numbers. Pins and sliding connections can be modeled by using springs of zero stiffness.

* LOAds (Any number of cards, each having 4 items of data.)

Will be used only if a STRess card is present.

Item

1 — Node reference number at which dead and/or live load is applied.

2 — Load direction. Values 1, 2 and 3 are forces, 4, 5 and 6 are moments, in the usual order of global coordinates (x, y and z or r, θ and z).

3 VD — Value of dead load.

4 VL — Value of live load.

* ACCeleration (One card containing three items of data)

Will be used only if a STRess card is present.

Item

1 to 3 — Acceleration components in the global x, y, and z directions respectively. Defaults are 0., 0., -386.

The ACCeleration card causes the effects of an applied acceleration (such as gravity) to be included in the stress analysis. If the card is input without data, the default values are used.

* TAPer (Any number of cards, each with 7 items of data.)

Item

1 — Reference number. Since the member being defined is a substructure, this is a substructure reference number which must not duplicate a stayed column or other substructure reference number. This reference number appears as the SUB entry on the MEMber data card that is referenced by the CONnection list.

2 — Member reference number that defines SECtion properties, PRElоad, and SPRing connections. (Other options on MEMber card are not allowed.)

3 L — Length. All occurrences of a substructure must have the same length. If the item is entered as zero, the length will be calculated from the first appearance in the CONnection list. However, a length must always be specified if the substructure forms part of a STEpped substructure.

4 NEL — If positive, defines the number of elements which will be used to approximate the tapered member. If negative, exact stiffnesses will be calculated with SECtion properties varying as in equation (3).

5 N Exponent n used in equation (3) defining property variation. N is ignored if $C \leq -1$.

6 C If $C > -1$, taper ratio c used in equation (3).
If $C \leq -1$, then absolute value of C is reference number of VARiation group used to describe a general taper.

7 Length ratio used to subdivide member length unequally for the general taper capability. A value of 1 or 0 will result in elements of equal length. Otherwise the value must lie between 0 and 2, and represents the ratio of the length of the first element to the average length (L/NEL). The lengths of subsequent elements vary arithmetically.

* VARiation (Any number of cards, each with 9 items of integer data.)

Used to specify general variation of section properties and axial load.

Item

1 Reference number.

2 to 9 A nonzero input refers to a PROfile reference number that will define the variation of section properties and axial load in the order EA, EIY, GJ, M, IP, EIX, PD, PL. If zero, the corresponding property or load is taken as constant.

* PROfile (Any number of cards and items of data.)

Used to define an equation which describes the variation of a section property or load along the length of a member. The resulting value is multiplied by a base value given in the SECtion properties or PREload card groups.

Item

1 Reference number.

2 to 2J+1 Pairs of numbers a_i, b_i such that if the reference number is positive, the profile is given by

$$\sum_{i=1}^{J} a_i \left(\frac{z}{L}\right)^{b_i}$$

where z is distance along a member (measured from the lower numbered of the connected nodes) and L is member length. If the reference number is negative, only one pair of numbers is entered and the profile is generated by raising profile a_1 to the power b_1.

* STEpped (Any number of cards and items of data.)

Used to link several previously defined substructures that are joined end to end to form a new substructure.

Item

1 Reference number of new substructure being created. This reference number appears as the SUB entry on a MEMber data card whose member number is used for the appearance of the substructure in the CONnection list.

2... Reference numbers of substructures defined either in the TAPer card group or previously in this card group. If a minus sign precedes a substructure reference number, the substructure is rotated 180 degrees such that its initial and final ends are reversed.

4.6.3 Plotting The following cards are used to obtain plots of the undeformed structure and modes from the eigenvalue analysis.

* PLOt (Two cards required, or one card with value of IPLOT as only entry if default values used for other variables.)

IPLOT, VERT, HORIZ, INTM, IDUP (First card, 5 items of data.)

IPLOT = 0 no plotting done

= 1 undeformed structure and mode shapes plotted as solid lines

= 2 undeformed structure plotted as dashed lines, mode shapes as solid lines

= 3 mode shapes only plotted as solid lines

= -5 undeformed structure only plotted, no analysis made.

VERT Vertical size of plot. Default value set in program at installation depending on scale of plotting device.

HORIZ Horizontal size of plot. Default same comment as for VERT.

INTM Number of interior points in each member for which the mode shape is calculated and plotted. For substructures, the interior shape is interpolated from end point displacements and rotations and is shown with a short and long dashed line. Default 0.

IDUP Structure repeats in a regular pattern for IDUP = 0; repeats in a staggered pattern for IDUP = 1. Default 0.

VIEW(1), VIEW(2), VIEW(3), AMP, IVERT, ROT (Second card, 6 items of data.)

VIEW(I)	Global x, y and z coordinates which locate the viewpoint from which the structure is seen. Rectangular coordinates are always used for VIEW(I), even if analysis is done in cylindrical coordinates. Defaults are 1 1 1.
AMP	Controls amplitude of mode shape relative to structure. Ordinarily is of order one. Default 1.
IVERT	Absolute value of IVERT is the global axis which will be vertical on plot before rotation by angle ROT. A positive value of IVERT gives a perspective projection from the view point. A negative value of IVERT gives a projection parallel to a line from origin to viewpoint. Default -3.
ROT	Angle in degrees by which the IVERT axis is rotated on plot. Positive in counterclockwise direction. Default 0.

4.6.4 Reset Capability A number of variables are seldom changed for different analyses and take on default values assigned in the program. If required they can be changed by using the RESet card. In addition, the variables in the CRIteria card group can be changed from their default values by the RESet card so it is not mandatory that the CRIteria data be input. If only a few variables need changing, it may be more convenient to use RESet cards. The variables that may be input through the RESet capability are listed below along with their default values. Users may wish to alter the source code (SUBROUTINE REED) to change the default values to others that are more commonly encountered. The RESet cards can appear more than once at arbitrary locations in the input. Care should be taken that subsequent data input does not overwrite a desired RESet value. The last occurrence of the data following a RESet card controls what the program uses.

* RESet (Special card(s) to change certain variables from their default values.)

VARIABLE	DEFAULT	
CF	1.E5	
FQ	1.	
FP	0.	
NDIV	0	
IDBUG	5	
IOFILE (Initialized in main program)	0	VAX
	1	CDC
IQL	0	
PDELTA	0.	
NE	0	
PR	.3	
SF	5/6	
SMASPR	0.	
NIMAX	9999	
NDMAX	5	
NFMAX	30	

A description of the variables not already defined is given below.

IDBUG	Causes certain diagnostic printing as indicated in the beginning of the source code.
IOFILE	Causes mode finding to be in core or out of core as follows:

IOFILE	
0	In core. Recommended for virtual memory machines
1	Uses direct access files
2	Uses sequential files

IQL	A nonzero value of IQL causes modifications of the stress analysis to be made as described in section 3.4. A value of 1 causes the Q/L terms to be added to the stiffness matrix. A value of 2 or 3 causes the stress analysis to be made with axial member stiffnesses only and all joints pin connected. For IQL = 2, all member preloads are ignored thus assuring that no transverse shear forces due to axial loading are present. This is required to ensure perfect (to machine accuracy) equilibrium. For IQL = 3, the member preloads are included in the stress analysis which may result in transverse shear forces to maintain equilibrium. No correction or change in the stress analysis is made if IQL = 0.
PDELTA	During an eigenvalue analysis all axial forces are multiplied by 1 ± PDELTA where the plus sign applies to tension forces and the minus sign applies to compression forces, see section 3.4.
NE	Number of earth or grounded nodes which must be given last in the coordinate list.
PR	Poisson's ratio.
SF	Global shape factor, used for any member that has a zero shape factor in the SECtion properties input.

Note that the transverse shear stiffness is given by

$$\frac{SF*EA}{2(1+PR)}$$

SMASPR	A spring of stiffness I*SMASPR will be placed at each translational degree of freedom where I ranges from 1 to 3 corresponding to the degree of freedom number. Used in structures having rigid body degrees of freedom to prevent ill-conditioning of the stiffness matrix. If modes are required and SMASPR is nonzero, the convergence procedure will determine as accurately as possible a set of linearly independent modes for the nearly zero eigenvalues.
NIMAX	Maximum number of iterations allowed is absolute value of NIMAX. If negative, the program prints the CPU time for each iteration.

NDMAX NFMAX	These variables affect the performance and storage requirements of the accelerated convergence procedure. If the default values are inappropriate for a particular problem, the program will print an explanatory message suggesting alternative values.

The default value of any of these variables may be changed with a RESet card. For example, CF and PR can be changed as follows:

```
RESET
CF = 1000. PR = .25
```

The = sign may be omitted if desired and data may appear on several lines.

<u>4.6.5 Automatic Data Generation</u> Additional cards may be generated from any input card by using the following format. If the items on an input card are x_1, x_2, x_3, .., then the sequence of cards

$$
\begin{array}{l}
\quad x_1 \quad x_2 \quad x_3 \quad \ldots \\
= (\Delta_1 x_1)\ (\Delta_1 x_2)\ (\Delta_1 x_3)\ \ldots \\
= (\Delta_2 x_1)\ (\Delta_2 x_2)\ (\Delta_2 x_3)\ \ldots \\
\cdots\cdots\cdots\cdots\cdots\cdots \\
= (\Delta_m x_1)\ (\Delta_m x_2)\ (\Delta_m x_3)\ \ldots \\
== (n_1) \\
== (n_2) \\
\cdots\cdots \\
== (n_m)
\end{array}
$$

produces $n_1 \times n_2 \times \ldots n_m$ cards. First the values of x_i are given and then incremented n_1-1 times by $\Delta_1 x_i$. All of these cards are incremented n_2-1 times by $\Delta_2 x_i$ and so on. Several examples of the use of this input are given in the example problems.

If the letter C precedes a Δx, a pattern where members form a closed loop will be generated as indicated in figure 5. The last item generated is $x-\Delta x$ rather than $x+(n-1)\Delta x$ which would be the case if the C were absent.

An additional feature allows modification of the size of the increments as well as the number of times they are executed. If the sequence xIy is enclosed by parentheses where x and y are numbers, the number x is incremented by y after each use. This facility can be used to generate triangular grids as shown in figure 6. By changing three numbers which are the number of nodes and members on a side, any size structure can be generated.

5 EXAMPLE PROBLEMS

The input requirements for several problems that illustrate most of the capabilities of the program are given in the following sections. For each problem, the input data file is given along with critical output that can be checked by a user duplicating the case at his own installation.

5.1 Simply Supported Stepped Beam

This example illustrates the basic input requirements of the program. The input data file is shown in table 1. Comments (text preceded by $) are used as prompts to identify various aspects of the input and are often useful when modifying data for a new problem. It is not necessary to enter zeros at the end of a data line that has a prescribed number of input items such as for SECtion properties. Here the last six items are not entered causing zeros to be input for these quantities. The zeros then cause the default values for IP, EIX, SFX, and SFY to be used. The structure is a simply supported planar beam having a change of beam properties occurring at a point 40 per cent along the length. In addition to the card PLAne frame, it is necessary to restrain the out of plane degrees of freedom at all nodes. This has been accomplished by a card that treats node 1, followed by cards employing the automatic data generation capability of the program to restrain all nodes. The input load is such that the buckling eigenvalue would be 1. if the properties were uniformly those of the more flexible portion. The eigenvalue is about 29 per cent greater than 1. and a plot of the mode shape shown in figure 7 shows less deflection of the stiffer left end of the beam. Note that it was not necessary to subdivide the beam into several elements to obtain the exact answer, and that the interior mode shape was also recovered exactly and plotted at ten interior points for each element of the beam by specifying INTM = 10 under the PLOt heading in the input. This problem could have been worked by creating a substructure consisting of the two different members but the interior mode shape would be approximate. The effect of transverse shear deformation can be included by adding a SET card with LS = 1 to the data of table 1. The result for this case is an eigenvalue of 1.2852.

5.2 Simply Supported Tapered Beam

This example is identical to the previous one except the beam is tapered. The properties at each end are identical to that of the previous problem with a linear variation of area and a cubic variation of inertias along the length. This is accomplished by the card group TAPer and the use of a single data card in the SECtion group and two data cards in the MEMber card group as shown in table 2. The eigenvalue for this case is 2.9406.

5.3 Truss with Central Load

This example illustrates that the stress analysis capability of the program provides the member loads used in the subsequent buckling analysis. The input data file is shown in table 3. The structure and loading is shown in figure 8(a). Extensive use of the automatic data generating capability of the program has been used to generate the geometry and connectivity of the structure. Changing just a few numbers that have to do with the number of bays of the structure is all that is required to generate a structure of any number of bays, and no additional lines of data are needed. The buckling mode shown in figure 8(b) shows that lateral instability of the upper compressive cord of the truss dominates. Due to round-off, the stress analysis gives very small axial forces in members that are actually unloaded. A diagnostic message is printed saying that these forces have been ignored in the buckling analysis.

5.4 Tower with Stayed Columns

This problem is identical to example 4 of the original BUNVIS user's guide (ref. 1). The input file is given in table 4. The coordinates are given as integers referring to the list of REAl numbers which requires inclusion of the INTeger data card in the input. The legs of the tower, shown in figure 9(a), are stayed columns of the two different types shown in figure 9(b). The connectivity and coordinates of the stayed columns are identified by cards beginning with SUB. The two buckling loads calculated are 1.7944 and 2.5205. The data, taken from reference 1, was not of sufficient accuracy that the length of the stayed columns matched to a high precision the distance between the connected nodes. A message indicating this discrepancy is part of the printed output.

5.5 Frame with Stepped and Tapered Members

This problem illustrates the input for stepped and tapered members including the specification of the orientation of the principal axes of members with unequal flexural rigidities. The bandwidth reduction feature has also been implemented for this problem. The input data file is shown in table 5 and the layout of the structure is shown in figure 10. It has a plane of symmetry but different means of specifying a member that appears in two or more different locations are used in the input. For instance the four tapered legs are specified four different ways: exact tapers and approximate profiled tapers, each with the small end first and also with the large end first. The substructuring capability is used to reverse members which were specified with their small end first. The two stepped members are specified in one case by introduction of two extra nodes (nodes 3 and 5 in figure 10) and in the other by the substructure method. In addition, the local x and y axes for these members have been interchanged but accounted for by specifying CT as the cosine of the angle between local x and global z as either 0. or .8. This angle is more difficult to calculate for the diagonal members so the alternative input is used which defines a third point given by a node number that lies in a plane containing the member longitudinal axis and the local x axis. The input data file would be much shorter and simpler if each unique member were specified only once in the most direct and simplest way rather than being duplicated many times in order to illustrate the capabilities of the program. The vibration modes show proper symmetry characteristics which a user can check, indicating the correctness of the different ways of specifying the member properties. In addition, identical members with different means of definition can be interchanged in the connection list without altering the fundamental vibration frequency of 1.1043.

5.6 Hexagonal Frame

The repetitive capability of the program is illustrated in this example which is discussed in detail in reference 16. A plan view of the repeating portion and various vibration mode responses of the complete structure are shown in figure 11. The input data file is given in table 6. Only inplane modes were obtained. The free vibration response is desired so none of the three inplane degrees of freedom are suppressed by the input. Using the n of equation (2), one of the rigid body modes occurs in the $n = 0$ harmonic and the other two are for $n = 1$. Since eigenvalues occur singly for $n = 0$ and in pairs for $n = 1$, all rigid body modes are obtained for a planar structure in the first eigenvalue of these two harmonics. By specifying eigenvalues starting at two under the EIGenvalues card, only elastic modes are obtained for $n = 0$ and 1. There are two nodes and two members in the repeating portion. The additional data required for repetitive structures is under the BAY information card, the MODes card, and the REPetition card. The ZJ(2) is the width of one bay in the second or θ coordinate direction. For cylindrical coordinates, rather than give the angle directly, the angle is determined from 2π/ZJ(2) or $2\pi/6$. The EN(2) is also 6. corresponding to the number of bays around the circumference to form the complete structure. The data under MODes specifies that results for harmonics from 0 to 1 will be determined. The data under REPetition specifies that the final end of member two is one bay removed from the basic repeating portion in the negative θ direction. For the modes involving primarily cable response (frequencies of 14.7 and 29.5 on figure 11), the input of AMP = 1. in the PLOt card group results in very large plotted deflections for the interior of the cable because normalization is based on maximum rotation which is essentially zero. To get acceptable results for such cases, a much smaller value of AMP is required that can be determined by trial and error.

5.7 Cable Stiffened Ring with Bicycle Spoke Lacing

This example problem is similar to that of reference 16 except that the hub area is modeled with eccentric connections to the spokes in order to illustrate that capability. The repeating portion and the complete structure are shown in figure 12. The input data is given in table 7. Additional features of this problem are a stress analysis of a repetitive structure due to pretension of the spokes and the use of the SMASPR input to remove ill-conditioning that might occur in the buckling analysis of a free structure with self equilibrating member loads. This problem gives a very low buckling load in harmonics 0 and 1 due to destabilizing forces resulting from a small error in equilibrium when considering only axial forces as discussed in section 3.4. The structure cannot be analyzed considering members as pin-ended because it has fewer members than are required for a statically determinate truss. Since the axial forces from the stress analysis are very close to being in equilibrium at each node, the PDELTA correction with a value of .01 was used to remove all low eigenvalues associated with rigid body modes. Angular coordinates are given in degrees by using the DEGree card. The values of the offsets are given in global coordinates (JCORD = 1). The offsets are at the final end of the cable so appear as the last three numbers on each card. The values of the offsets are given by

$$E2(1) = r \cos \theta$$

$$E2(2) = r \sin \theta$$

where r is the radius of the hub where all spokes are attached and θ is the angular coordinate of the point of attachment. The hub attachment of each spoke either leads or lags the rim attachment by 80°. Determining the lowest buckling load in harmonics 0 through 4 assures that the lowest buckling load of the complete structure has been found, which for this problem is 12.961 for n = 4.

5.8 Simply Supported Hexahedral Truss Platform

The repeating portion and the structure to be analyzed are shown in figure 2. The input data is shown in table 8. This problem illustrates a structure that is repetitive in two directions and contains pin-ended members. It is desired to have simply supported boundary conditions for a square platform with 8 bays on a side. Nodes indicated by dots are along the lines of simple support. Modes that repeat over 16 bays produce simply supported boundary conditions for an 8-bay platform. This platform has symmetry such that modes corresponding to harmonic m, n have the same frequency as harmonic m, -n. It can be shown that these two modes can be combined to give simply supported boundary conditions. If the stiffening was skewed or biased in one direction, or had loadings been present that cause asymmetrical member forces, the frequency for the m, n mode would not be equal to the m, -n mode and the two modes could not be combined. The mode would exhibit skewed nodal lines that would not conform to the desired rectangular boundaries.

There are four nodes in the repeating portion and the connectivity is such that some members project beyond the rectangular boundary of the complete structure which was generated by indexing the repeating portion eight bays in each direction. All members are pin ended so that SPR in the MEMber properties is 1 referring to the SPRing connections card. The data following the SPRing card indicates spring connections at five rotational degrees of freedom. The value of the spring constant is taken from the first number in the REAl number list which gives a zero spring stiffness. One torsional degree of freedom is rigidly connected to prevent zero frequency torsion modes of individual members from appearing. A small nonzero IP for each member prevents the torsional inertia from affecting the results. The parameter LC under the SET card is set to 1 to restrain all global rotational freedoms since the individual members have no rotational stiffness.

The complete structure cannot be generated by simply indexing the repeating portion independently in the two inplane coordinate directions. Similar nodes occur in a staggered pattern on both surfaces. To obtain correct plots of the structure, IDUP in the PLOt card group must be set to 1.

The first vibration mode and frequency are calculated for harmonic responses one through three in the x coordinate direction in combination with each harmonic response one through five in the y coordinate direction. The frequency for the fundamental mode (first harmonic in both directions) is 4.4439.

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Table 1.- Input For Simply Supported Stepped Beam

```
$ EXAMPLE 1: SIMPLY SUPPORTED STEPPED BEAM
PLANE FRAME
BUCKLING
EXPLANATION            $EXPANDED DESCRIPTION OF HEADINGS FOR CERTAIN OUTPUT
COORDINATES
1 0. 0. 0.  2 40. 0. 0.  3 100. 0. 0.
CONNECTION LIST
1 2 2  2 3 1
DOF RESTRAINED
1 0 0  3 0 0            $ DISPLACEMENTS AT EACH END ZERO
1 3 0  1 4 0  1 5 0     $ OUT-OF-PLANE DISPLACEMENTS ZERO AT NODE 1
$ THE FOLLOWING TWO DATA CARDS WILL CAUSE THE PREVIOUS DATA CARD TO APPEAR
$ THREE TIMES WITH NODE NUMBERS INCREMENTED BY ONE TO RESTRICT OUT-OF-PLANE
$ DISPLACEMENTS AT ALL THREE NODES
= (1) (0) (0) (1) (0) (0) (1) (0) (0)
== (3)
MEMBER DATA
$REF NO  SEC PRE REP OFF SPR SUB
    1      1   1
    2      2   1
SECTION PROPERTIES
$REF NO EA EIY GJ M IP EIX CT SFX SFY
    1    1. 1.  .5
    2    2. 8.  4.
PRELOADS
$REF NO  PD         PL
   -1     0. -9.869604401E-4
PLOT
$IPLOT VERT HORIZ INTM IDUP
   2     4.    6.   10
$VIEW(1) VIEW(2) VIEW(3) AMP IVERT ROT
   0.       0.      1.    3.    -2
```

Table 2.- Input For Simply Supported Tapered Beam

```
$ EXAMPLE 2: SIMPLY SUPPORTED TAPERED BEAM
PLANE FRAME
BUCKLING
COORDINATES
1 0. 0. 0.  2 100. 0. 0.
CONNECTION LIST
1 2 1
DOF RESTRAINED
1 0 0  2 0 0               $ DISPLACEMENTS AT EACH END ZERO
1 3 0  1 4 0  1 5 0        $ OUT-OF-PLANE DISPLACEMENTS ZERO AT NODE 1
= (1) (0) (0) (1) (0) (0) (1) (0) (0)
== (2)
MEMBER DATA
$REF NO  SEC PRE REP OFF SPR SUB
    1     0   0   0   0   0   1
    2     2   1
SECTION PROPERTIES
$REF NO EA EIY GJ M IP EIX CT SFX SFY
    2   2. 8.  4.
TAPER
$REF NO  MEMBER  LENGTH  NEL   N     C   LENGTH RATIO
   1       2       0.    -1    1.    -.5
PRELOADS
$REF NO  PD          PL
   -1    0. -9.869604401E-4
PLOT
$IPLOT VERT HORIZ INTM IDUP
   2    4.    6.   10
$VIEW(1) VIEW(2) VIEW(3) AMP IVERT ROT
   0.      0.      1.    3.   -2
```

Table 3.- Input For Truss With Central Load

```
$ EXAMPLE 3: TRUSS WITH CENTRAL LOAD
STRESS
BUCKLING
COORDINATES
1 0. 0. 0.  2 0. 10. 0.          $ COORDINATES OF NODES 1 AND 2
= (2) (10.) (0.) (0.) (2) (10.)  $ INCREMENT NODES BY 2, AND X BY 10.
== (11)                          $ REPEAT 11 TIMES
CONNECTION LIST
1 3 1              $ CORD MEMBERS
= (1) (1)
= (2) (2)
== (2)
== (10)
2 3 1              $ LEFT DIAGONALS
= (2) (2)
== (5)
11 14 1            $ RIGHT DIAGONALS
= (2) (2)
== (5)
1 2 1              $ VERTICALS
= (2) (2)
== (11)
DOF RESTRAINED
1 0 0  2 0 0
21 0 0  22 0 0
MEMBER DATA
1 1
SECTION PROPERTIES
1 2.E9 2.E7 1.E7
LOADS
$NODE DIRECTION  VD    VL
  12     2       0.   -1.E5
PLOT
2 4. 6. 5
-1. .5 -1. 5. -2
```

Table 4.- Input For Tower With Stayed Columns

```
$ EXAMPLE 4: TOWER WITH STAYED COLUMNS
INTEGER
BUCKLING
SECTION PROPERTIES
$REF  EA  EIY  GJ  MASS/L  POLAR I/L  EIX  CT  SFX  SFY
1 .24E10 .38E8 .3E8
2  .35E9 .13E6 .1E6
3 .64E9 .77E6 .6E6
4 .22E9
5 .74E8
6 .15E9
7 .75E8
8 .1E10 .4E11 .75E9
```

Table 4.- Concluded

```
MEMBER DATA
1 1 1
2 2
= (1) (1)
==(7)
9 0 0 0 0 0 1
10 0 0 0 0 0 2
PRELOAD
-1 0. -.1E7
REAL NUMBERS
0. 2.3817 47.6182 30.8040 17.9898 16.6666 15.3434
3.1945 5.75 49.9999 99.9998
12.5 10.83 21.65 99.2 6.25 .5E5 .1E6
EIGENVALUES
-1 -2
CONNECTION LIST
SUB 1
1 3 3  1 4 7  1 6 6  2 3 1  3 4 1  4 5 1  4 6 5  5 6 2
5 7 1  6 7 2  6 8 4  7 8 1
COORDINATES
SUB 1
1 9 1 10  2 1 1 10  3 1 1 3  4 1 1 4  5 1 1 5  6 8 1 6  7 1 1 7  8 1 1 1
CONNECTION LIST
SUB 2
1 2 2  1 4 3  1 6 7  1 8 6  2 3 2  2 4 2  3 5 1  4 5 3  5 6 1
6 7 1  6 8 5  7 8 2  7 9 1  8 9 2  8 10 4  9 10 1
COORDINATES
SUB 2
1 9 1 10  2 2 1 10  3 1 1 10  4 2 1 3  5 1 1 3  6 1 1 4
7 1 1 5  8 8 1 6  9 1 1 7  10 1 1 1
CONNECTION LIST
1 2 8  1 3 8  1 4 9  1 5 10  2 3 8  2 4 10  2 6 9  3 5 9  3 6 10
COORDINATES
1 -12 14 15  2 1 1 15  3 12 14 15  4 -16 13 1  5 1 14 1
EARTH NODE
6 16 13 1
DOF RESTRAINED
4 1 -17  4 2 -18  4 3 0  5 0 0
STAY FRAMES
3 4
PLOT
2 4. 6. 3 0
3. 2. 1. 1. -3 0.
```

Table 5.- Input For Frame With Stepped And Tapered Members

```
$ EXAMPLE 5: FRAME WITH STEPPED AND TAPERED MEMBERS
VIBRATION
BAND
CRITERIA
1.0E6 1.0 -4
SECTION PROPERTIES
$   EA     EIY      GJ        M        IP       EIX     CT
1  2.0E9 2.0E7    1.0E7    1.0E2    3.0E0    4.0E7    0.   $SMALL END
2  2.2E9 2.662E7 1.331E7   1.1E2    3.993E0 5.324E7  0.   $BIG END
3  2.0E9 2.0E7    1.0E7    1.0E2    3.0E0    4.0E7    2    $THIRD POINT NODE 2
4  2.0E9 2.0E7    1.0E7    1.0E2    3.0E0    4.0E7    1    $THIRD POINT NODE 1
5  2.0E9 4.0E7    1.0E7    1.0E2    3.0E0    2.0E7    .8   $SMALL, X-Y REVERSED
6  2.2E9 5.324E7 1.331E7   1.1E2    3.993E0 2.662E7  .8   $BIG, X-Y REVERSED
MEMBER DATA
1 1                           $ UNIFORM SMALL
2 2                           $ UNIFORM BIG
3 0 0 0 0 0 2                 $ EXACT C=-0.09090909
4 0 0 0 0 0 7                 $ EXACT C=.1 TURNED AROUND
5 0 0 0 0 0 4                 $ PROFILED C=-0.09090909
6 0 0 0 0 0 8                 $ AUTO. PROFILED C=.1 TURNED AROUND
7 0 0 0 0 0 10                $ STEPPED SYMMETRIC
8 3                           $ DIAGONAL 1-4
9 4                           $ DIAGONAL 2-6
10 5                          $ UNIFORM SMALL, X-Y REVERSED
11 6                          $ UNIFORM BIG, X-Y REVERSED
CONNECTION LIST
1 2 1   4 6 1                 $ UNIFORM HORIZONTALS
1 3 1   3 5 2   5 6 1         $ EXPLICIT STEPPED SYMMETRIC SLOPING SIDE
2 4 7                         $ SUBSTRUCTURED STEPPED SYMMETRIC SLOPING SIDE
1 7 3   2 8 4                 $ EXACT TAPERED VERTICAL
4 9 5   6 10 6                $ PROFILED TAPERED VERTICALS
1 4 8   2 6 9                 $ DIAGONALS
COORDINATES
1 0. 0. 10.  2 10. 0. 10.  3 0. 5. 13.75
4 10. 20. 25.  5 0. 15. 21.25  6 0. 20. 25.
EARTH
7 0. 0. 0.  8 10. 0. 0.  9 10. 20. 15.  10 0. 20. 15.
PROFILES
1 1.0 0.0 -0.09090909 1.0          $ 1 - 0.09090909*Z/L
-2 1 3.0                           $ (1 - 0.09090909*Z/L)**3
VARIATION
$  EA EIY GJ M  IP EIX PD PL
1  1   2  2  1  2   2
TAPER
$ MEM  L   NEL  N    C
1  1  10.  -1   1   .1                    $ EXACT C=.1
2  2  10.  -1   1   -0.09090909   0.      $ EXACT C=-0.09090909
3  1  10.  20   1   .1            1.      $ AUTO. PROFILED C=0.1
4  2  10.  20   0   -1            1.      $ PROFILED C=-0.09090909
5 10   6.25                               $ UNIFORM SMALL
6 11   6.25                               $ UNIFORM BIG
```

Table 5.- Concluded

```
STEPPED
7     -1                                $ EXACT C=0.1 TURNED AROUND
8     -3                                $ AUTO. PROFILED C=0.1 TURNED AROUND
9     5     6                           $ HALF OF STEPPED SYMMETRIC MEMBER
10    9     -9                          $ STEPPED SYMMETRIC MEMBER
PLOT
2 4. 6. 5 0
4. -2. 1. 1. -3 0.
```

Table 6.- Input For Hexagonal Frame

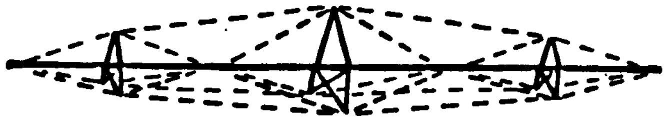
```
$ EXAMPLE 6: HEXAGONAL FRAME
PLOT
2 4. 6. 3 0
3. 2. 1. 1. -3 0.
VIBRATION
PLANE FRAME
SET
$  ICORD LC LR LS
2
CRITERIA
$  CF   FQ FP NDIV
1.E6 5.
SECTION PROPERTIES
1 2.2903E7 76.680 113.28 .8756
2 1.687E5 0 0 .008756
PRELOADS
-1 -7.568
-2 7.568
MEMBER
1 1 1
2 2 2 1
EIGENVALUES
-2 -3
CONNECTION LIST
1 2 1  2 2 2
COORDINATES
1 0 0 0  2 1 0 0
DOF RESTRAINED
1 3 0  1 4 0  1 5 0
2 5 0  2 3 0  2 4 0
BAY INFORMATION
$ZJ(1) ZJ(2) ZJ(3) EN(1) EN(2) EN(3)
  0.    6.    0.    1.    6.    1.
MODES
$NL1 NU1 NL2 NU2 NL3 NU3
  0   0   0   1                        $RESPONSE IN HARMONICS 0, 1
REPETITION
$FINAL END OF MEMBER IS DISPLACED 1 BAY IN THE NEGATIVE THETA DIRECTION
1 0 -1 0
```

Table 7.- Input For Cable Stiffened Ring With Bicycle Spoke Lacing

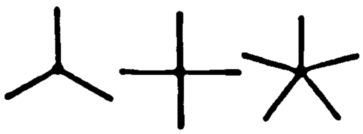
```
$ EXAMPLE 7: CABLE STIFFENED RING WITH BICYCLE SPOKE LACING
BUCKLING
INTEGER
STRESS
DEGREE
RESET
SMASPR=.1E-5
PDELTA=.01
SECTION PROPERTIES
1 .2873680E4 .0 .0 .9785800E-4 .0
2 .1034525E7 .448175E+2 .34476E+2 .3522888E-1 .0
MEMBER DATA
1 1 1 0 1
2 1 1 0 4
3 1 1 0 2
4 1 1 0 3
5 2
6 2 0 1
REAL NUMBERS
0. 5.972239166 1.0530669 10. 20. 30.
CONNECTION LIST
1 2 5  1 4 6  1 5 1  2 3 5  2 6 3
3 4 5  3 5 4  4 6 2  5 6 5
COORDINATES
1 2 1 1  2 2 4 1  3 2 5 1  4 2 6 1  5 1 1 3  6 1 1 -3
BAY INFORMATION
0. 9. 0. 1. 9. 1.
MODES
0 0 0 4
REPETITION
1 0 -1 0
PRESTRAINS
1 0. .0001979
OFFSETS OF MEMBERS
$  MEMBER  JCORD  E1(1)  E1(2)  E1(3)  E2(1)  E2(2)  E2(3)
1 1 0. 0. 0. .05185342239 .2940753717 0.
2 1 0. 0. 0. 0. .2986119583 0.
3 1 0. 0. 0. .1493059792 -.2586055418 0.
4 1 0. 0. 0. .1919440669 -.2287500313 0.
PLOT CARDS
$  IPLOT VERT  HORIZ  INTM IDUP
$  VIEW(1)  VIEW(2)  VIEW(3)  AMP IVERT  ROT
2 4. 6. 7  0
0. 0. 1. 1. -2 0.
EIGENVALUES
-1
SET
2
```

Table 8.- Input For Simply Supported Hexahedral Truss Platform

```
$ EXAMPLE 8: SIMPLY SUPPORTED HEXAHEDRAL TRUSS PLATFORM
INTEGER INPUT
VIBRATION
SET
$ ICORD LC LR LS
1 1
SECTION PROPERTIES
1 3585000 224062.5 172304.1 .1384 .1E-7
2 717000 44812.5 34460.8 .02768 .1E-7
3 5736000 358500. 230700. .22144 .1E-7
MEMBERS
1 1 0 0 0 1
=(1) (0) (0) (1) (0) (0)
== (6)
7 2 0 0 0 1
=(1) (0) (0) (1) (0) (0)
== (4)
11 3 0 0 0 1
12 3 0 5 0 1
13 3 0 3 0 1
14 3 0 6 0 1
15 3 0 4 0 1
REAL NUMBERS
0 7.5
CONNECTION LIST
1 3 1  1 3 2  1 3 3  1 3 4  1 1 5
1 1 6  1 4 7  1 2 7  1 2 8  1 2 9
1 2 10  2 2 12  2 2 13  2 4 11  2 4 12
2 4 14  2 4 15  2 3 7
COORDINATES
1 1 1 1  2 1 2 2  3 1 2 1  4 1 1 2
BAY INFORMATION
7.5 7.5 0. 16. 16. 1.
MODES
$  NL1  NU1  NL2  NU2  NL3  NU3
1 3 1 5 0 0
REPETITION
1 1 -1 0
2 0 -2 0
3 -1 -1 0
4 1 1 0
5 -1 1 0
6 0 2 0
SPRING CONNECTIONS
1 0 0 0 1 1 0 0 0 0 1 1 1
PLOT
2 4. 6. 0 1
1000. 1000. 100. 1. 3 0.
```



(a) Column with N = 3.



(b) End views for N = 3, 4, or 5.

(c) Representative half frame.

Figure 1.- Typical stayed column substructure.

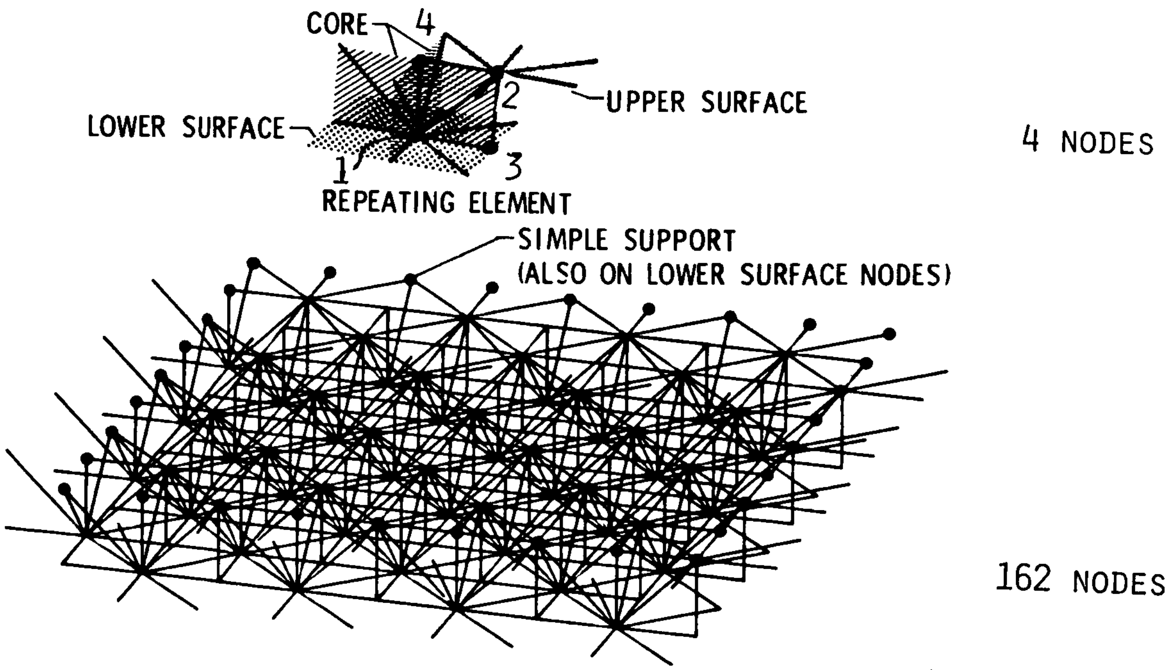


Figure 2.- Simply supported hexahedral truss platform illustrating repetition in two directions.

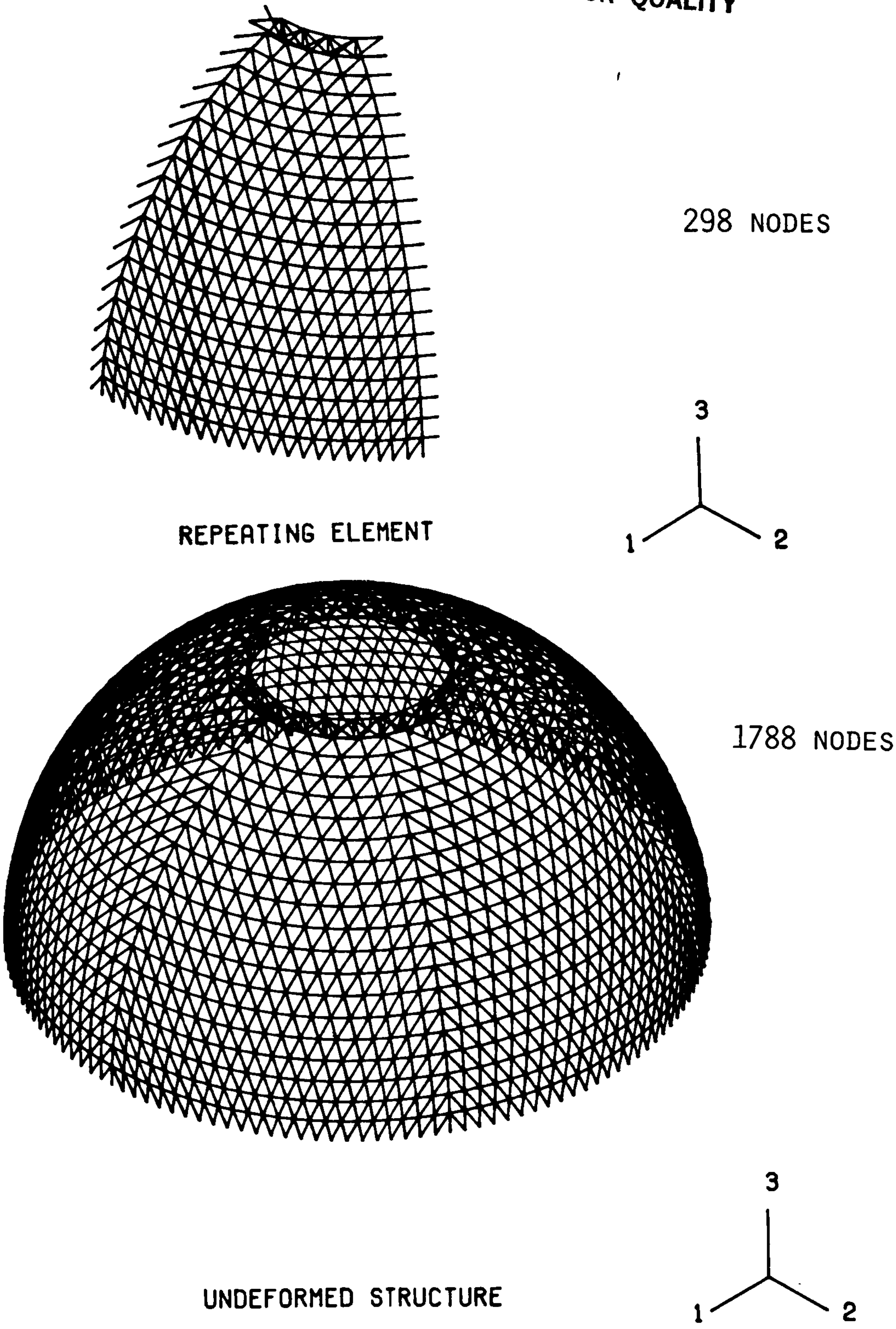
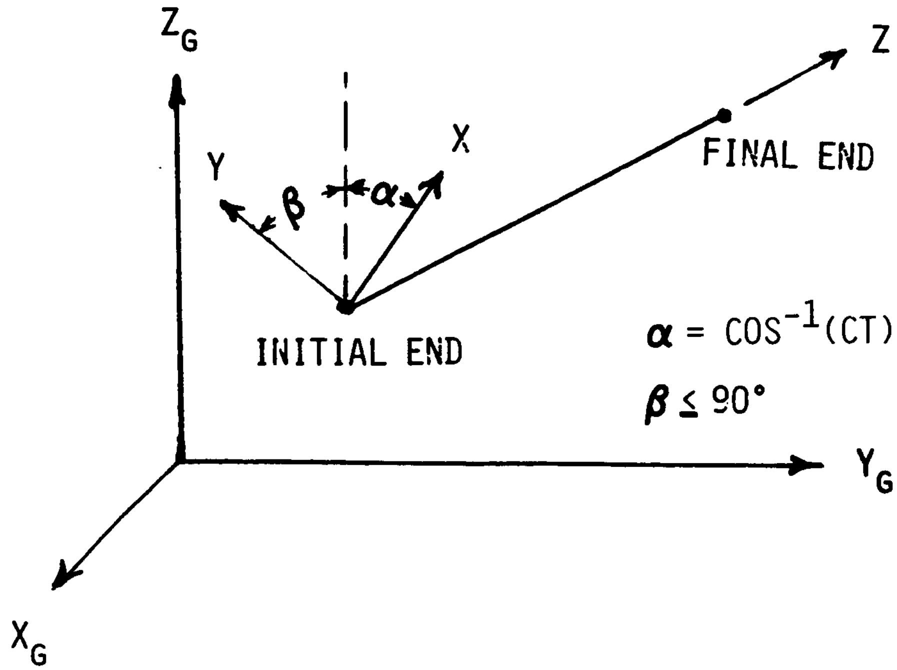
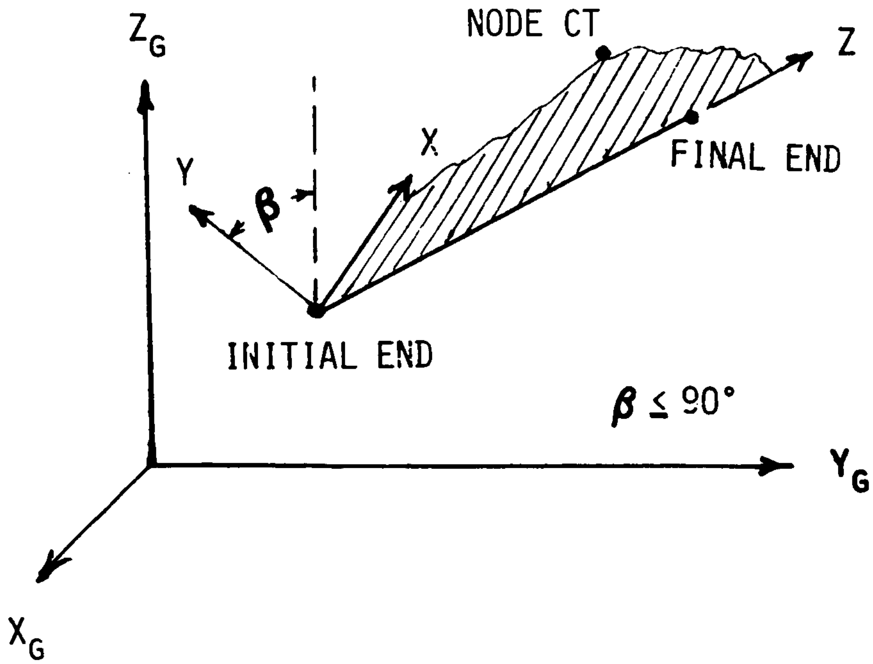


Figure 3.- Dome structure with stiffened hole illustrating rotational periodicity.



(a) CT < 1.



(b) CT ≥ 1.

Figure 4.- Local member coordinate system illustrating use of CT to orient the x and y axes.

```
CONNECTIVITY
    1   2   1
= (1) (C1)
== (5)
```

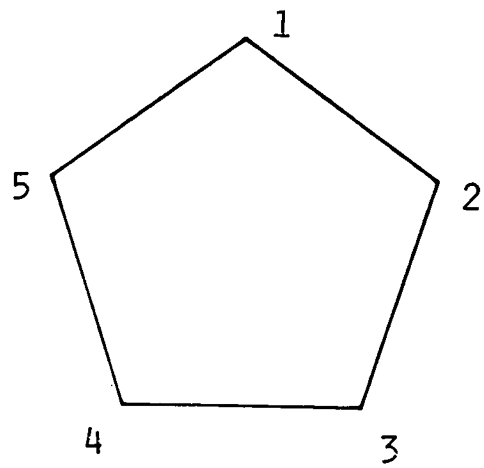
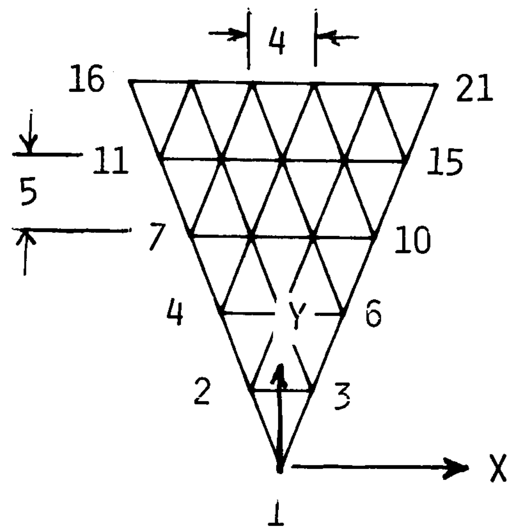


Figure 5.- Automatic generation of a closed loop structure.




```
COORDINATES
    1    0.    0.    0.
=  (1)  ( 4.)
= (1I1) (-2.) (5.)
== (1I1)
== (6)                $NUMBER OF NODES ON A SIDE
CONNECTIVITY
    1      2      1   $SLANTED MEMBERS
=  (0)    (1)
=  (1)    (1)
= (1I1) (2I1)
== (2)
== (1I1)
== (5)                $NUMBER OF MEMBERS ON A SIDE
    2      3      2   $HORIZONTAL MEMBERS
=  (1)    (1)
= (2I1) (2I1)
== (1I1)
== (5)                $NUMBER OF MEMBERS ON A SIDE
```

Figure 6.- Illustration of incrementing feature of automatic data generation capability applied to a triangular grid.

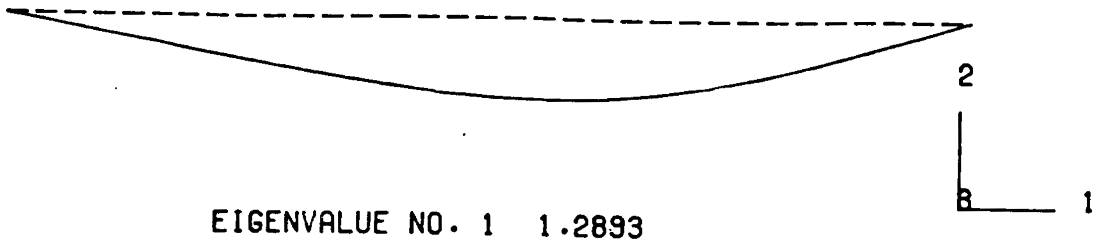
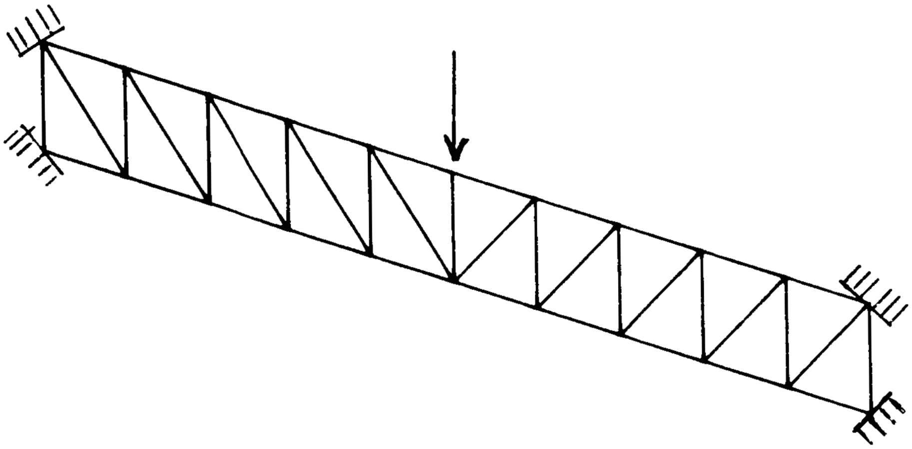
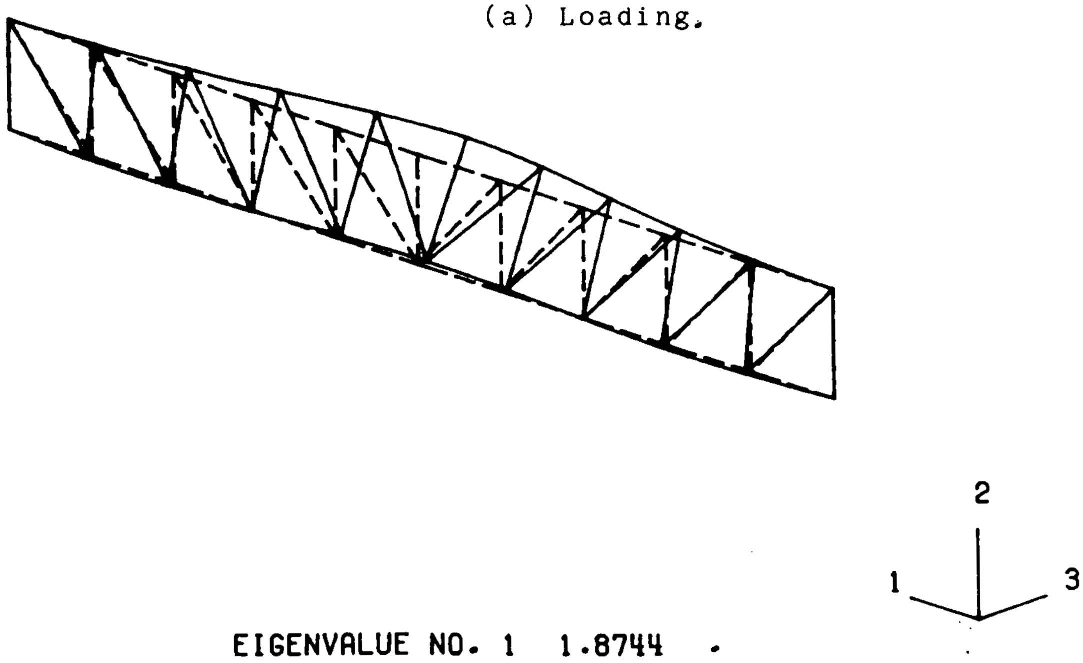


Figure 7.- Buckling mode of simply supported stepped beam.

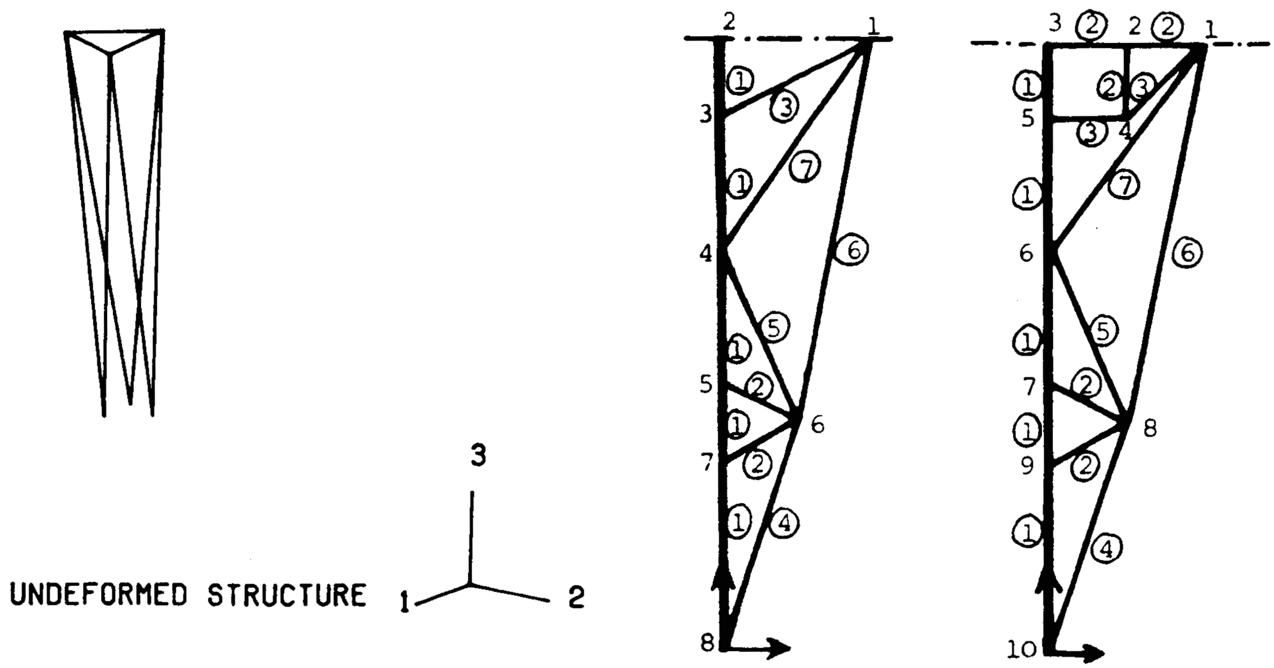


(a) Loading.



(b) Buckling mode.

Figure 8.- Truss with central load.



(a) Tower configuration. (b) Stayed columns.

Figure 9.- Tower with stayed columns.

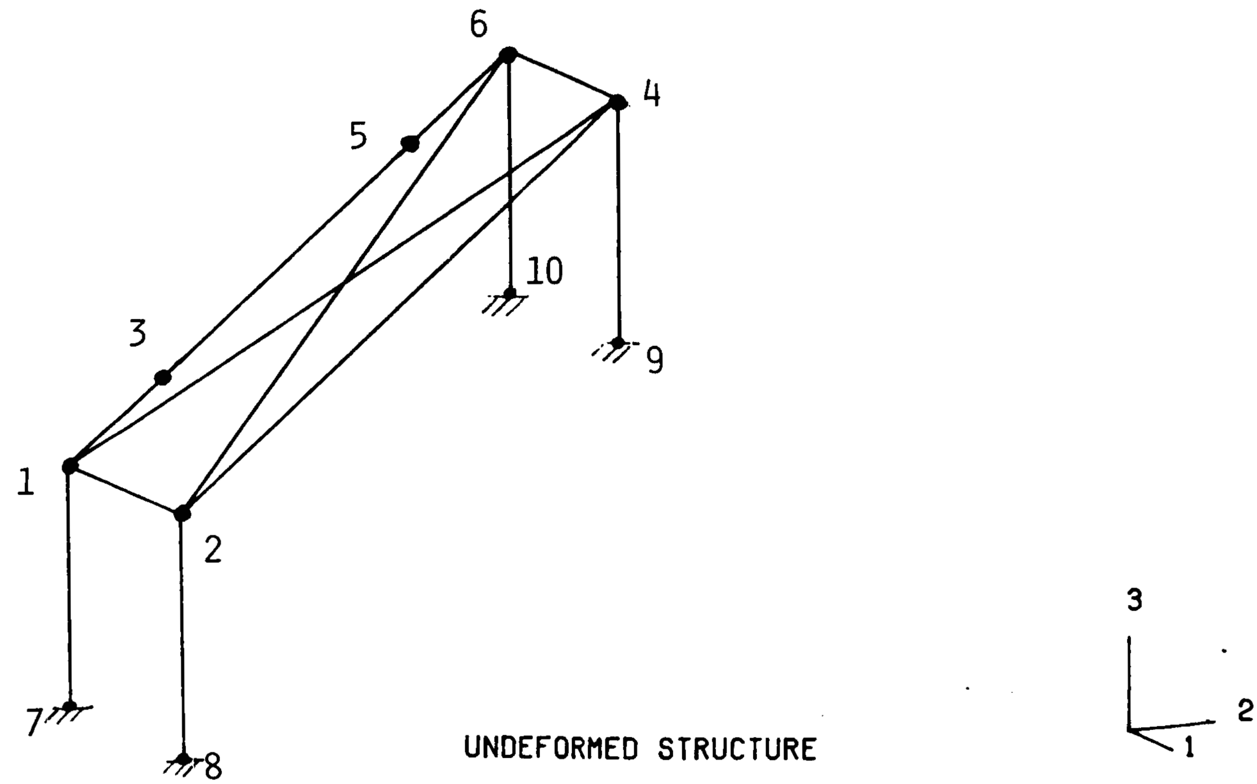


Figure 10.- Frame with stepped and tapered members.

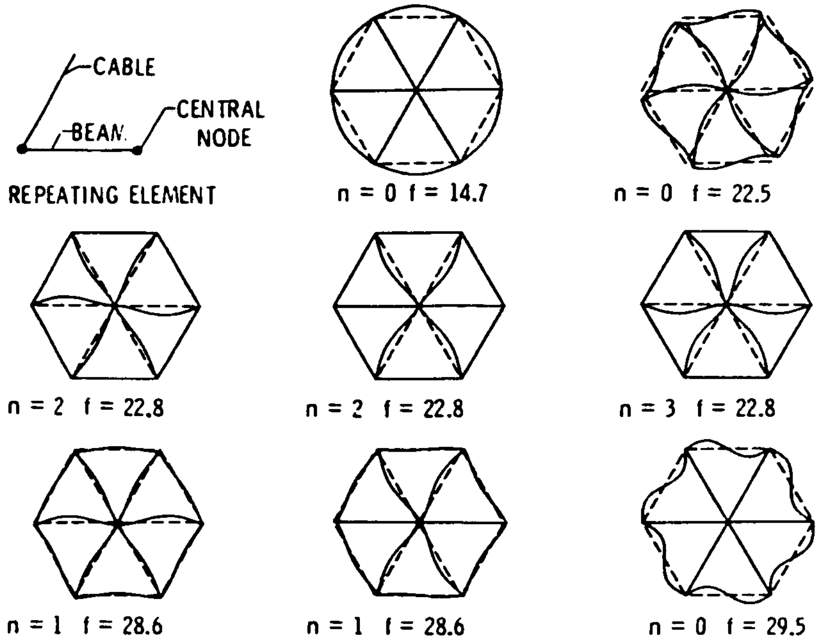


Figure 11.- Vibration modes of hexagonal frame.

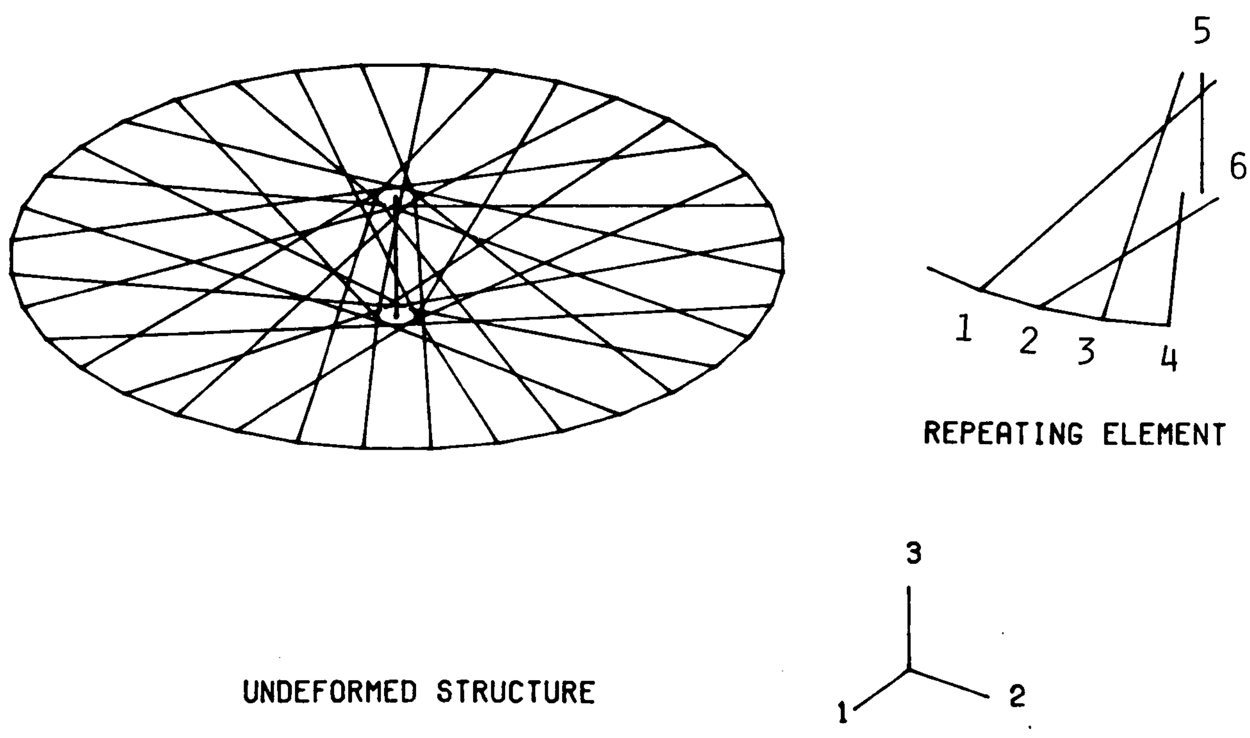


Figure 12.- Cable stiffened ring with bicycle spoke lacing.

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16. Abstract

A computer program is described which is especially suited for making vibration and buckling calculations for prestressed lattice structures that might be used for space application. Structures having repetitive geometry are treated in a very efficient manner. Detailed instructions for data input are given along with several example problems illustrating the use and capability of the program.

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