Nasa-CR-177,927

NASA Contractor Report 177927

NASA-CR-177927
19850022054

APPLICATION OF THE ADAMS PROGRAM TO DEPLOYABLE SPACE TRUSS STRUCTURES

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Contract NAS1-18000
July 1985

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National Aeronautics and
Space Administration
Langley Research Center
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Section 1

SUMMARY

The need for a computer program to perform kinematic and dynamic analyses of large truss structures while deploying from a packaged configuration in space led to the evaluation of several existing programs. ADAMS (Automatic Dynamic Analysis of Mechanical Systems), a generalized program for performing the dynamic simulation of mechanical systems undergoing large displacements, is applied to two concepts of deployable space antenna units. One concept is a one-cube folding unit of Martin Marietta's Box Truss Antenna and the other is a tetrahedral truss unit of a Tetrahedral Truss Antenna.

The purpose of this report is to describe the ADAMS program and discuss the problems and results of its application. In addition, a supplementary method for estimating surface member bending stresses at latch-up is described. Realistic surface member latch-up forces cannot be produced by the present version of ADAMS as it is limited to the assembly of rigid bodies. Future versions should solve this problem with a flexible body code. Results in this report include member displacement and velocity responses during extension and an example of member bending stress at latch-up.

Section 2

INTRODUCTION

The concept of deploying antenna truss structures in space from packaged configurations as opposed to the erection of such structures by assembling the parts while in space requires the capability to perform kinematic and dynamic analyses of mechanical systems composed of many parts. A search for existing programs which might be evaluated for this purpose revealed several programs. Of these, ADAMS (Automatic Dynamic Analysis of Mechanical Systems) (ref. 1) showed the most promise. Application of this program to the dynamic simulation of the deployment of two space antenna units is discussed in this report. A unit can be viewed as one of many building blocks which form an antenna. One concept is a one-cube folding unit of Martin Marietta's Box Truss Antenna (ref. 2) and the other is a tetrahedral folding unit of a Tetrahedral Truss Antenna (ref. 3). Simulation was accomplished on the VAX 11/780 computer through the time-sharing services of Mechanical Dynamics, Inc. (MDI), Ann Arbor, Michigan.

Other programs were considered for application. IMP (Integrated Mechanisms Program) was developed at the University of Wisconsin and is now available through General Electric CAE International, Inc. DADS (Dynamic Analysis and Design Systems) was developed at the University of Iowa. This program has only recently become commercially available. The rigid body code can now be purchased from Computer Aided Design Software, Inc., Oakdale, Iowa. Flexible body code should be available in the year 1986. DISCOS (Dynamic Interaction Simulation of Controls and Structures) developed by Martin Marietta Corporation under the auspices of NASA Goddard Space Flight Center, is a program designed for mechanical systems with flexible bodies. This program has the reputation for being rather unwieldy to use, especially for systems with many parts. Available documentation was difficult to translate to application. SNAP (no acronym) is a proprietary program developed by General Dynamics, Corp., Convair Division, San Diego, California, for their Geo-Truss Antenna and is, therefore, not available.

The ADAMS program is described in Section 3. It was chosen for application primarily based on the strong position that the developer, MDI, has in the commercial market and the availability of user documentation, training classes, consultation services, and time-sharing facilities. The present version is limited to assembly of rigid bodies which seriously limits member force analysis. There is a need to determine dynamic forces in the folding members when they latch-up to the extended position. This capability should become available when MDI completes the flexibility code in 1986. In the interim, however, estimates of surface member bending stresses at latch-up can be made by considering the surface member flexibility and kinetic energy in a separate analysis. A method such as this is described in Section 4.

Results of the dynamic simulations during extension are limited to the displacement and velocity responses of the box truss unit and to the displacement response of the tetrahedral truss unit. A discussion of the input procedures, modeling problems, and output results for each antenna unit is given in Sections 5 and 6.

Section 3

DESCRIPTION OF ADAMS

ADAMS, developed by Mechanical Dynamics Inc. (MDI), is a three-dimensional program which determines the time response of contiguous rigid bodies undergoing large displacements. Two bodies are contiguous if they are in actual contact by virtue of a force as with various forms of joints. The joint type specifies the number of constraints between the two bodies. A string of bodies may be connected so as to form closed loops, open loops or no loops.

There are five separate analysis modes in the ADAMS program (ref. 1):

1) Kineto-static
2) Static Equilibrium
3) Dynamic (Stiff Integration)
4) Dynamic (Non-Stiff Integration)
5) Quasistatic

The term kineto-static (ref. 4) is an expression used by MDI which is synonymous with the strict definition of the term, kinematic, as opposed to the often imprecise connotation referring to any system undergoing large geometric changes. This mode of analysis is applicable only to zero degree of freedom systems containing generators. In general, motion generators acting on a translational or revolute joint cause the system motion from which related displacements, velocities, accelerations, and forces are solved. It is an algebraic solution and no differential equations are solved. Therefore, this mode of analysis is not only faster but also more accurate than the dynamic mode.

The static equilibrium analysis is applicable to all mechanical systems having non-negative degrees of freedom. ADAMS will try to determine the configuration of the system where the system forces are in equilibrium at zero velocity and acceleration.

To perform a dynamic or transient analysis, the system must have degrees of freedom greater than zero. The analysis, described in ref. 4 and 5, involves the simultaneous solution of differential equations with specified constraints. Fifteen first-order differential equations generated for each part are derived by combining the second order differential equations of motion and algebraic constraint equations with the addition of Lagrange multipliers. The Lagrange multipliers enable a solution of constraint (joint reaction) forces. The typical differential equations to be solved will be "stiff" and are therefore assumed by default. A stiff system is one with widely separated eigenvalues and the Gear algorithm is used for integration. The Adams-Moulton algorithm is used for a non-stiff integration. Both algorithms use a predictor-corrector procedure with variable order and variable step size.

For those problems where there is no interest in the temporal variation of variables such as displacement or velocity, the system should be simulated in the quasistatic mode. It is essentially a sequence of static equilibrium analyses performed on the system at different points in time. An example is the determination of the angle of a tilt table test stand at which it becomes unstable and tips over.

The Grubler mobility criterion (ref. 6) is an essential, but not necessarily sufficient method for determining the three-dimensional system degrees of freedom during assembly. The criterion as applied to the ADAMS program is written in the following form:

DOF = 6*(PARTS-1)-5*(TRA+REV)-4*(CYL+UNI)-3*(SPH+PLA)-1*(GEN+RACK+SCREW+UMCON)

where TRA, REV, etc. each equal an appropriate degree of freedom. The RACK and SCREW joints as well as the generator (GEN) and user written marker constraints (UMCON) are considered to each have a single constraint (ref. 1). When the DOF is less than zero, the system has no mobility and is a structure which causes ADAMS to halt execution. When DOF is zero, a kineto-static solution with system generators is assumed. When DOF is greater than zero, a force responsed dynamic simulation is assumed.

Input statements construct a model in ADAMS composed of parts, markers, joints, forces, generators, system parameters, and graphic elements. Output requests, necessary output control statements and other special features described in ref. 1 are also included in the input. The part statement must specify the part center of mass, marker identification number, and mass moments of inertia. The parts are referenced by markers which specify initial locations and orientations. A marker is a point and an orthogonal triad of unit vectors forming a local coordinate system fixed with respect to the part. It is also used to define joints, forces and for graphic display. Standard forces are either constant or vary linearly but non-linear forces can be described by writing a function subprogram.

Eight types of joints are accepted by ADAMS. They are in order of degrees of freedom: revolute (1), translational (1), screw (1), rack-and-pinion (1), cylindrical (2), universal (2), spherical (3), and planar (3). As mentioned before, the screw and rack-and-pinion are considered single constraint joints. Initial displacements and velocities can be specified on the revolute and translational joints through the part statements.

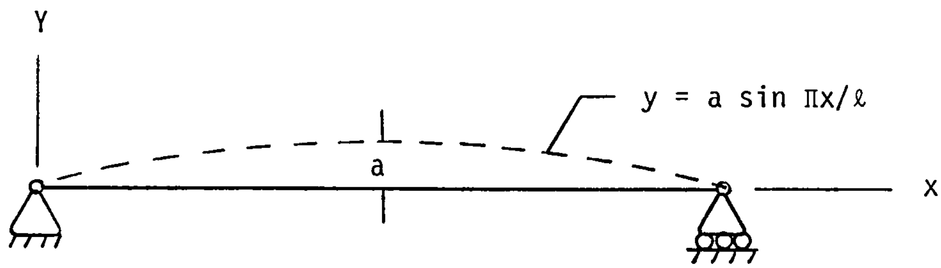
Only the dynamic analysis mode (stiff integration) is illustrated in this report, although five static analyses were performed on the tetradehral truss unit to fold the unit into a position to begin the dynamic simulation of its deployment. The simulations are initiated by a "transient" command after which ADAMS displays the current value of time as TBEGIN and requests the final time (TEND) and the number of output steps (NSTEPS). Requested output is printed at intervals equal to (TEND-TBEGIN)/NSTEPS.

Section 4

MEMBER LATCH-UP BENDING STRESSES

The bending moments in the unfolding members as they latch-up into the extended position are the most significant dynamic member forces during the deployment condition. The lack of a flexible body code for computing these forces requires an alternate method. The following presents a method for estimating the member bending stresses at latch-up.

A free body of the member after latch-up is shown as follows:



The member is assumed a simple beam with constant cross-section, pinned at each end and vibrating after latch-up in the first bending mode. Rigid body kinetic energy at latch-up is assumed to transfer to bending strain energy at maximum deflection. Reference 7, in the chapter for energy methods, gives the following expression for energy in a vibrating simple beam:

$$KE = \frac{w}{2g}\,\omega^2 \int_0^{\ell} y^2 dx \qquad (1)$$

where

KE = kinetic energy
w = weight/unit length
g = acceleration of gravity
ω = fundamental frequency, radians/sec
y = mode shape function = $a \sin \Pi x/\ell$
ℓ = beam length

Substituting the mode shape, a half sine wave, integrating and solving for the maximum deflection gives,

$$a = \frac{2}{\omega} \sqrt{\frac{(KE)g}{w\ell}} \tag{2}$$

The fundamental frequency (ref. 7) for a simple beam is:

$$\omega = \Pi^2 \sqrt{\frac{EIg}{w\ell^4}} \tag{3}$$

where

E = modulus of elasticity

I = beam section area moment of inertia

Substituting Equation (3) in Equation (2) gives the beam deflection,

$$a = \frac{2}{\Pi^2} \sqrt{\frac{(KE)\ell^3}{EI}} \tag{4}$$

With this deflection, the bending moment and stress can be obtained. Ideally, the inertial load distribution is in the form of a half sine wave, but the assumption of a uniformly distributed load gives excellent results. The standard equations for deflection and bending moment (ref. 8), respectively, are:

$$a = \frac{5w\ell^4}{384EI} \tag{5}$$

$$M = \frac{w\ell^2}{8} \tag{6}$$

Substituting Equations (5) and (6) in Equation (4), and solving for M gives,

$$M = 1.95 \sqrt{\frac{(KE)EI}{\ell}} \tag{7}$$

For a thin circular section the beam moment of inertia (I) and section modulus(S), respectively, are $\pi R^3 t$ and $\pi R^2 t$. Substituting these expressions and Equation (7) in the standard formula, fb = M/S, the bending stress is:

$$fb = 1.95 \sqrt{\frac{(KE)E}{\pi \ell R t}} \tag{8}$$

where

R = tube radius

t = tube thickness

Accuracy of this method depends on the accuracy of the kinetic energy. If there are significant energy losses before latch-up which cannot be neglected, the kinetic energy can be determined from the velocities of the significant masses at latch-up or the values of the losses must be at least estimated and subtracted from the potential energy. Assuming small losses, the energy can be based on the work done by the deployment forces. If significant, the deployment force would include, for example, the known frictional forces. It is assumed that the deployment forces are confined to each unit with little energy transfer to adjacent units. For example, the box truss and tetrahedral truss surface members are assumed to unfold by a linear spring (see Section 5) over an angle of approximately 180 degrees. Without losses, a conservative assumption, the energy is then equal to 168 in lb - the area under the torque profile curve. In the case of the box truss unit, the latch-up bending stress from Equation (8) is 12,700 lb/in^2. This is based on a graphite/epoxy tubular member with $E = 20 \times 10^6$ lb/in^2, R = 1.64 in, t = .026 in and ℓ = 590.56 in and is a comfortably low stress for the material.

Section 5

BOX TRUSS UNIT

Figure 1(a) shows the stowed antenna after removal from the Orbiter. As indicated, the 15 meter box truss units are extended one row at a time progressing along the feed mast and then along the reflector until fully deployed as shown in figure 1(b).

The diagonals in each frame are cords composed of individual graphite/epoxy strands. Since the diagonals in a frame are not tensioned until the frame is fully extended, they are not included in the model shown in figure 2 and are assumed to have negligible influence on the deployment other than the fact that as the diagonals are tensioned near the full extension position, some kinetic energy will be absorbed.

Figure 2 shows the model of the box truss surface member. The numbers in squares are part numbers. On of the two superimposed reference frames is the global or ground reference frame and the other is the part reference frame and both are superimposed by default when the vector, OG, locating the part reference frame is omitted from the part statement.

Joint friction is assumed to be zero. All members are considered to be rigid bodies. Assuming all frames in a row will extend at the same rate, only one frame need be analyzed. By symmetry, the frame model can be reduced to one surface member (parts 3 and 4) and two dummy parts (parts 2 and 5) to constrain the motion of points 2 and 4 as they would be constrained with the full frame model. In addition, the dummy members represent the concentrated adjacent antenna masses.

The geometry for the model of the box truss unit in the folded position is given in table 1. Included are comments defining each type of joint. This is a two-dimensional problem being solved in a three-dimensional program, so a spherical joint was chosen for point 3 to provide sufficient degrees of freedom for a forced response simulation. A revolute joint would have caused the model to be over-constrained. Had the problem been solved with the two-dimensional program, DRAM (Dynamic Response of Articulated Machinery) discussed in ref. 5, a revolute joint could have been used. The mass and mass moments of inertia for the components are given in table 2. Note that the model is slightly open in the folded position. Table 3 is the input file. In the first attempt to run the problem, the initial position of the model was such that points 2 and 4 were coincident with point 6. Though this simplified input preparation and allowed an even 90 degrees of motion, ADAMS halted execution, and the output indicated a singular matrix. A slightly open position was tried and execution was successful as shown in tables 4 through 6.

Energy for deployment is assumed to be stored in a linear torsion spring in the joint at point 3 with a torque profile having a maximum torque of 80 in-lbs in the folded position to 27 in-lbs in the extended position acting over an angle of 180 degrees. This is input into the program with the force statement shown in the input file, table 3, after calculating by hand the parameters, KT and A. The keyword for this force is GTORQUE (GT) and is linearly dependent on the relative rotation and relative angular velocity (if damping is present) of the part markers. The torque equation is:

$$T = -CT(d\alpha/dt)-KT(\alpha-A)+T'$$

where

- T = torque exerted on part 3 marker by part 4 marker (in-lb) (positive in a counterclockwise sense).
- CT = viscous damping coefficient (in-lb/rad/sec).
- KT = torsional spring constant (in-lb/degree).
- A = angle of spring under zero load (degrees)
- T' = torque of constant magnitude.
- α = relative angle between markers not to exceed 180 degrees.

The variables, T, α and $d\alpha/dt$ are computed automatically by ADAMS.

The sensor statement in the input file causes the computations to halt when the parts are horizontal and the truss unit is fully extended. At this time, the relative angle between markers 0303 and 0403 is 178 degrees with an error of 1 degree. Note the output comments at the bottom of table 4 giving the time of 89.55 seconds at which this event occurred.

The output for request number 1 is in table 5. The request was for the relative displacement between marker 0303 and marker 0106. Marker 0303 is located on part 3 at point 2 and marker 0106 is located on part 1, the ground, at point 6. This output shows the magnitude of the position vector varying from the initial value of 5 to the maximum value, the part length.

Request number 3 (REQ/3) shown in table 3 asks for the relative velocity between the marker 0202 located on part 2 at point 2 and marker 0302 located on part 3 at point 2. The output shown in table 6 shows both the relative translational and angular velocities. Since the two marker origins are located in the same revolute joint, the small values of translational velocity are due to numerical error. The maximum angular velocity is shown to be .65 radians/sec.

Figures 3, 4 and 5 show the position of the two surface member parts at times 0.0, 85 and 89.55 seconds, respectively. In figures 4 and 5, the display exceeds the graphic field on two views, but clearly show the symmetrical displacement of points 2 and 4 as it should be with equal masses at these points.

Section 6

TETRAHEDRAL TRUSS UNIT

Figure 1(a) shows the stowed antenna after removal from the Orbiter. As indicated, the 15 meter box truss units are extended one row at a time progressing along the feed mast and then along the reflector until fully deployed as shown in figure 1(b).

The diagonals in each frame are cords composed of individual graphite/epoxy strands. Since the diagonals in a frame are not tensioned until the frame is fully extended, they are not included in the model shown in figure 2 and are assumed to have negligible influence on the deployment other than the fact that as the diagonals are tensioned near the full extension position, some kinetic energy will be absorbed.

Figure 2 shows the model of the box truss surface member. The numbers in squares are part numbers. On of the two superimposed reference frames is the global or ground reference frame and the other is the part reference frame and both are superimposed by default when the vector, OG, locating the part reference frame is omitted from the part statement.

Joint friction is assumed to be zero. All members are considered to be rigid bodies. Assuming all frames in a row will extend at the same rate, only one frame need be analyzed. By symmetry, the frame model can be reduced to one surface member (parts 3 and 4) and two dummy parts (parts 2 and 5) to constrain the motion of points 2 and 4 as they would be constrained with the full frame model. In addition, the dummy members represent the concentrated adjacent antenna masses.

The geometry for the model of the box truss unit in the folded position is given in table 1. Included are comments defining each type of joint. This is a two-dimensional problem being solved in a three-dimensional program, so a spherical joint was chosen for point 3 to provide sufficient degrees of freedom for a forced response simulation. A revolute joint would have caused the model to be over-constrained. Had the problem been solved with the two-dimensional program, DRAM (Dynamic Response of Articulated Machinery) discussed in ref. 5, a revolute joint positions served the same purpose - to attach the model to ground. Components of the acceleration of gravity were set to zero in the system statement (table 11) as in a space environment, but the attachment to ground is still required during the static equilibrium solution.

Tables 9, 10, and 11 are the command file, the function subprogram, and the input file, respectively. Note that all statements in the input file which are indented five or more spaces to the right are in effect deleted as they are not interpreted as data cards. These statements could have been edited from the file but were left there for the record. The command file resets the three knee-joint torques, 90607, 90910, and 91213 so that the static equilibrium commands will fold the truss to the desired position. After this, the torque parameters are reset back to the values shown in the input file. Note that the parameters, A and T' in the force statements are equal to zero and -27, respectively. The torque profiles are the same as used for the box truss unit but with opposite sign. This is necessary, since the markers are oriented differently. Following this, the ground to upper fitting torques, 1427, 1497, and 1498 (ref. tables 9 and 11) are reset with zero spring rates which in effect disconnects the ground to fitting torque constraints. Translational separation from ground to fitting is automatic at time greater than zero by the function subprogram. The next six commands cause the calculated forces to be printed. The final command, TRAN, causes computation of the dynamic simulation for 3 seconds with 90 steps.

The function subprogram (table 10) computes the forces (FSUB) for the corresponding forces 1426, 1428, and 1429 acting between the upper fitting and ground (see figures 6 and 7 and table 11) during static equilibrium when the time is equal to zero. It also computes the damping torques (TSUB) for the corresponding forces, 80607, 80913, and 81213 acting in the knee-joints during the dynamic simulation when the time is, of course, greater than zero and when PHI is less than or equal to 10 degrees. Referring to table 10 in FSUB, APAR(1), APAR(2), and APAR(3) are the x, y, and z relative displacements, respectively, of marker I and marker J defined in each force statement. PAR(1) is a spring rate equal to 100 lbs/in (from table 11). For TSUB, PAR(1) is equal to 10 degrees and is also obtained from the corresponding force statement in table 11. ADAMS converts this angle to radians. PHI, in radians, is the angle between the x-axes of marker I relative to marker J. DPHI, in radians/second, is the corresponding angular velocity. PAR(2) and PAR(3) are viscous damping coefficients equal to 1,000 in-lb/rad/sec.

The purpose of the additional torques from TSUB is to provide heavy damping in the knee-joints to brake the angular motion to a quick stop at the fully deployed position. This method was designed by the MDI consultant, who resolved the modeling problem discussed earlier. The advantage of this method over the use of a sensor (see box truss unit discussion) is that computations can continue past the latch-up time (1.7 sec) up to the specified limit (3.0 sec). The additional time frames were used in a video display of the deployment, a copy of which was provided to NASA/Langley. Had there been a reason for the latch-up to occur on some sort of spring (other than the members which must be rigid), the impact response, with appropriate input modifications, might have been simulated.

A limited reproduction of the output from request no. 9999 made in the input file is shown in table 12. It is the relative displacement response of marker 806 on part 8 to marker 906 on part 9 (see figure 6) expressed in the coordinate system of marker 806. It can be seen from the 806 marker statement in table 11 that the Euler angles rotate the marker triad 90 degrees about its x-axis such that the z-axis is in the plane of figure 6 pointing toward part 7. The z-axis for marker 906 is in the same position but its x-axis is almost perpendicular to the figure at time equal to zero seconds resulting in the relative angle between x-axes as -89.50 degrees. As the deployment progresses the angle approaches zero degrees, the theoretical latch-up angle at a time near 1.7 sec. A graphical sequence of this is shown at four points in time in figure 8 through 11.

Section 7

CONCLUDING REMARKS

ADAMS is considered the best available three-dimensional general-purpose program for performing large-displacement, kinematic, and dynamic analyses of a mechanical system, such as a deploying space antenna. According to reference 1, ADAMS was designed to accommodate problems of virtually any size. However, solving a problem the size of a Tetrahedral Truss Antenna should be demonstrated. CPU time can be estimated by extrapolation. If not by extrapolation of actual data from a series of problems, a rough estimate of CPU time can be made by assuming the time to increase as the 1.5 to 2nd power of the number of equations (ref. 1) or the number of parts since the number of equations are related to the number of parts. Ultimately, though, the limitation must be determined by application.

ADAMS is excellent for solving static equilibrium problems and also kinematic problems involving, for example, the observation of certain moving parts for possible interferences or other functional considerations. Deployment position, velocity and acceleration time histories are accurately determined in the dynamic analysis mode. Excellent graphical and video displays can be created from the position time histories.

Since ADAMS is a rigid body program, there is a limit in the scope of dynamic analysis. For example, deployment latch-up forces cannot be determined due to the absence of flexible members to absorb the kinetic energy. A new version of ADAMS, which should be available in the year 1986, will include a flexible body code and should be able to determine latch-up forces. A disadvantage of this code is the potential for huge increases in computer time. This problem is alleviated by limiting the number of flexible bodies in the model. As discussed in Section 4, a relatively simple alternate method of analysis is easily developed for estimating the maximum surface member bending stresses by considering the surface member flexibility and kinetic energy at latch-up in the first bending mode.

Large problems which make the flexible body code impractical to use may make it desirable to develop a special-purpose program for a particular antenna design.

General Dynamics' SNAP program is an example of a special-purpose program. Rather than develop a general-purpose program based on rigorous large displacement dynamics for almost any mechanical system, the development was based on a deployable truss structure in mind and idealizing the members as lumped masses connected by springs and dampers. Satisfactory results are obtained for the kinematics of deployment and the elastic response at latch-up. As the development of a large computer code is expensive, the limited use of a general-purpose program such as ADAMS might be employed before making the necessary commitment to a particular design.

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Table 1. - Box Truss Geometry Data, Folded Position

Point	X(IN.)	Y	Z	Comment
1	5.0	0.	0.	Translational joint
2	600.0	0.	0.	Revolute joint
3	605.0	-295.28	0.	Spherical joint
4	610.0	0.	0.	Revolute joint
5	1205.0	0.	0.	Cylindrical joint
6	605.0	0.	0.	Reference point
0300	602.5	-147.64	0.	CM of Part 3
0400	607.5	-147.64	0.	CM of Part 4

Table 2. - Box Truss Component Data

Component	Data
02 Lumped Mass	Mass = 3.6 lb sec^2/in. IP = .01 .01 .01
03 Surface Member	Mass = .0122 IP = 88.64 1.0 88.64
04 Surface Member	Mass = .0122 IP = 88.64 1.0 88.64
05 Lumped Mass	Mass = 3.6 IP = .01 .01 .01

Note: IP = IX IY IZ (lb sec^2 in)

TABLE 3. - INPUT FILE FOR BOX TRUSS MEMBER.

```
BOXTRUSS FOLDING MEMBER,FREE-FREE CONDITION

PART/01,GROUND
MA/0101,QP=5,0,0,EU=90,90,0
MA/0105,QP=1205,0,0,EU=90,90,0
MA/0106,QP=605,0,0

PART/02,MASS=3.6,CM=0202,IP=.01,.01,.01
MA/0201,QP=5,0,0,EU=90,90,0
MA/0202,QP=600,0,0

PART/03,MASS=.0122,CM=0300,IP=88.64,1,88.64
MA/0300,QP=602.5,-147.64,0
MA/0302,QP=600,0,0
MA/0303,QP=605,-295.28,0

PART/04,MASS=.0122,CM=0400,IP=88.64,1,88.64
MA/0400,QP=607.5,-147.64,0
MA/0403,QP=605,-295.28,0
MA/0404,QP=610,0,0

PART/05,MASS=3.6,CM=0504,IP=.01,.01,.01
MA/0504,QP=610,0,0
MA/0505,QP=1205,0,0,EU=90,90,0

        JOINTS,DOF=2 W/O GEN
JO/0102,TRA,I=0101,J=0201
JO/0203,REV,I=0202,J=0302
JO/0304,SPH,I=0303,J=0403
JO/0405,REV,I=0404,J=0504
JO/0501,CYL,I=0505,J=0105

        FORCE
FO/1,CT,I=0303,J=0403,KT=.2944,A=271.74,T=0,CT=0

SENSOR/34,DISP,I=0303,J=0403,ANG1
,VALUE=178D,PRINT,HALT,EQ,ERROR=1.0D

        GRAPHICS
GR/1,OUT=0302,0303
GR/2,OUT=0403,0404

        OUTPUT
REQ/1,DIS,I=0302,J=0106
REQ/2,DIS,I=0404,J=0106
REQ/3,VEL,I=0202,J=0302,RM=0202

        SYSTEM CARDS
SYS/GC=1.,IGRAV=0,JGRAV=0,KGRAV=0

        OUTPUT CARDS
OUTPUT/SAVEREQ,GRSAVE
END
$
```

TABLE 4. - INTERACTIVE TERMINAL DISPLAY AFTER LOADING AND EXECUTING.

```
ADAMS
Enter ADAMS input-file name (or QUIT): BOXTM.FRE;14
Enter run-name for output files (<CR>=BOXTM):
Enter subroutine binary-file name (<CR>=none):
Do you have your own linked version of ADAMS (Y/N) (<CR>=N):
Do you want to run in batch mode? (Y/N) (<CR>=N):
Send output to terminal? (Y/N) (<CR>=N):
Begin execution of ADAMS....

 ENTERING INPUT PHASE

      BOXTRUSS FOLDING MEMBER,FREE-FREE CONDITION

NUMBER OF EQUATIONS IN JACOBIAN =    98
CPU TIME =      1.770 SECONDS
ENTERING SIMULATION PHASE
ENTER SIMULATION COMMAND
TRA

NEQ=   46 NG=  298 MAXNUM=  8797


NEQ=   98 NG=  516 MAXNUM= 13029

TBEGIN= 0.00000E+00 ENTER TEND, NSTEPS
95 190

TIME= 2.50000D-02 H= 2.50000D-02 KFLAG= 1 ORDER= 1 IFCT=     1 ISTP=     5
TIME= 9.50000D+00 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=    47 ISTP=    31
TIME= 1.90000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=    85 ISTP=    50
TIME= 2.85000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   123 ISTP=    69
TIME= 3.80000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   161 ISTP=    88
TIME= 4.75000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   199 ISTP=   107
TIME= 5.70000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   237 ISTP=   126
TIME= 6.65000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   275 ISTP=   145
TIME= 7.60000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   315 ISTP=   164
TIME= 8.55000D+01 H= 5.00000D-01 KFLAG= 1 ORDER= 2 IFCT=   372 ISTP=   183
****NOTE(EVNCHK) - SENSOR/   34  IS ACTIVE
EVENT VALUE =   3.10669E+00  SENSOR VALUE =   3.09078E+00   TIME =  8.95545E+01
ADAMS EXECUTION TERMINATED BY SUBROUTINE SENACT

   78.070 CPU SEC.
FORTRAN STOP
ADAMS output file is: BOXTM.OUT
ADAMS Graphics file is: BOXTM.GRA
ADAMS Request file is: BOXTM.REQ
$
```

TABLE 5. - OUTPUT FOR BOX TRUSS MEMBER, REQUEST NO. 1.

BOXTRUSS FOLDING MEMBER,FREE-FREE CONDITION
REQUEST NUMBER 1

DISPLACEMENT OF MARKER 302 RELATIVE TO MARKER 106

TIME	MAG	X	Y	Z	PSI	THETA	PHI
0.0000	5.000	-5.000	0.000	0.000	0.000	0.000	0.000
0.5000	5.009	-5.009	0.000	0.000	0.002	0.000	0.000
1.0000	5.038	-5.038	0.000	0.000	0.007	0.000	0 000
1.5000	5.085	-5.085	0.000	0.000	0.016	0.000	0.000
2.0000	5.150	-5.150	0.000	0.000	0.029	0.000	0.000
2.5000	5.235	-5.235	0.000	0.000	0.046	0.000	0.000
3.0000	5.338	-5.338	0.000	0.000	0.066	0.000	0.000
3.5000	5.460	-5.460	0.000	0.000	0.089	0.000	0.000
4.0000	5 601	-5.601	0.000	0.000	0.117	0.000	0.000
4.5000	5.761	-5.761	0.000	0.000	0.148	0.000	0.000
5.0000	5.940	-5.940	0.000	0.000	0.182	0.000	0.000
5.5000	6.137	-6.137	0.000	0.000	0.221	0.000	0.000
6.0000	6.353	-6.353	0.000	0.000	0.262	0.000	0.000
6.5000	6.588	-6.588	0.000	0.000	0.308	0.000	0.000
7.0000	6.841	-6.841	0.000	0.000	0.357	0.000	0.000
7.5000	7.113	-7.113	0.000	0.000	0.410	0.000	0.000
8.0000	7.404	-7.404	0.000	0.000	0.467	0.000	0.000
8.5000	7.714	-7.714	0.000	0.000	0.527	0.000	0.000
9.0000	8.042	-8.042	0.000	0.000	0.590	0.000	0.000
9.5000	8.390	-8.390	0.000	0.000	0.658	0.000	0.000
10.0000	8.755	-8.755	0.000	0.000	0.729	0.000	0.000
83.0000	254.634	-254.634	0.000	0.000	58.597	0.000	0.000
83.5000	257.624	-257.624	0.000	0.000	59.763	0.000	0.000
84.0000	260.634	-260.634	0.000	0.000	60.980	0.000	0.000
84.5000	263.666	-263.666	0.000	0.000	62.258	0.000	0.000
85.0000	266.720	-266.720	0.000	0.000	63.605	0.000	0.000
85.5000	269.796	-269.796	0.000	0.000	65.032	0.000	0.000
86.0000	272.895	-272.895	0.000	0.000	66.556	0.000	0.000
86.5000	276.017	-276.017	0.000	0.000	68.198	0.000	0.000
87.0000	279.163	-279.163	0.000	0.000	69.988	0.000	0.000
87.5006	282.333	-282.333	0.000	0.000	71.974	0.000	0.000
88.0000	285.529	-285.529	0.000	0.000	74.233	0.000	0.000
88.5000	288.748	-288.748	0.000	0.000	76.917	0.000	0.000
89.0000	291.982	-291.982	0.000	0.000	80.404	0.000	0.000
89.5000	295.106	-295.106	0.000	0.000	86.838	0.000	0.000
89.5545	295.312	-295.312	0.000	0.000	88.644	0.000	0.000

TABLE 6. - OUTPUT FOR BOX TRUSS MEMBER, REQUEST NO. 3.

BOXTRUSS FOLDING MEMBER,FREE-FREE CONDITION
REQUEST NUMBER 3

VELOCITY OF MARKER 202 RELATIVE TO MARKER 302
EXPRESSED IN THE COORDINATE SYSTEM OF MARKER 202

TIME	VM	DX/DT	DY/DT	DZ/DT	WM	WX	WY	WZ
0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.5000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.5000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3.5000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4.0000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	-0.001
4.5000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	-0.001
5.0000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	-0.001
5.5000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	-0.001
6.0000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	-0.002
6.5000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	-0.002
7.0000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	-0.002
7.5000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	-0.002
8.0000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	-0.002
83.0000	0.004	-0.004	0.002	0.000	0.040	0.000	0.000	-0.040
83.5000	0.005	-0.005	0.002	0.000	0.041	0.000	0.000	-0.041
84.0000	0.006	-0.005	0.002	0.000	0.043	0.000	0.000	-0.043
84.5000	0.007	-0.007	0.002	0.000	0.046	0.000	0.000	-0.046
85.0000	0.008	-0.008	0.003	0.000	0.048	0.000	0.000	-0.048
85.5000	0.010	-0.010	0.003	0.000	0.051	0.000	0.000	-0.051
86.0000	0.013	-0.013	0.004	0.000	0.055	0.000	0.000	-0.055
86.5000	0.017	-0.017	0.004	0.000	0.059	0.000	0.000	-0.059
87.0000	0.024	-0.023	0.005	0.000	0.065	0.000	0.000	-0.065
87.5000	0.010	-0.010	0.002	0.000	0.073	0.000	0.000	-0.073
88.0000	0.017	-0.017	0.003	0.000	0.085	0.000	0.000	-0.085
88.5000	0.003	-0.003	0.000	0.000	0.104	0.000	0.000	-0.104
89.0000	0.014	-0.013	0.001	0.000	0.145	0.000	0.000	-0.145
89.5000	0.000	0.000	0.000	0.000	0.448	0.000	0.000	-0.448
89.5545	0.005	-0.005	0.000	0.000	0.653	0.000	0.000	-0.653

TABLE 7. - TETRAHEDRAL GEOMETRY DATA, OPEN POSITION.

Point	X(IN.)	Y	Z	Comment
1	0.0	-1.25	243.179	Bushing force
2	-1.083	0.625	243.179	Bushing force
3	1.083	0.625	243.179	Bushing force
4	-148.375	83.788	0.00	Revolute joint
5	-148.917	85.978	1.77	Revolute joint
6	-146.750	86.603	0.00	Revolute joint
7	0.00	86.603	0.00	Revolute joint
8	146.750	85.603	0.00	Revolute joint
9	148.917	85.978	1.77	Revolute joint
10	148.375	83.788	0.00	Revolute joint
11	75.00	-43.301	0.00	Revolute joint
12	1.625	-170.390	0.00	Revolute joint
13	0.00	-171.955	1.77	Revolute joint
14	-1.625	-170.390	0.00	Bushing force
15	-75.00	-43.301	0.00	Revolute joint
16	0.00	0.00	244.949	Marker origin, upper fitting
17	0.00	0.00	243.179	Marker origin, upper fitting
18	-150.00	86.603	0.00	Marker origin, lower fitting
19	150.00	86.603	0.00	Marker origin, lower fitting
20	0.00	-173.205	0.00	Marker origin, lower fitting
0100	0.00	0.00	244.199	Upper fitting CM
0200	-75.00	43.302	124.975	Diagonal CM
0300	75.00	43.302	124.975	Diagonal CM
0400	0.00	-86.603	124.975	Diagonal CM
0500	0.00	-173.205	0.750	Lower fitting CM
0600	-38.313	-106.846	0.00	Surface member CM
0700	-111.688	20.244	0.00	Surface member CM
0800	-150.00	86.603	0.75	Lower fitting CM
0900	-73.375	86.603	0.00	Surface member CM
1000	73.375	86.603	0.00	Surface member CM
1100	150.00	86.603	0.75	Lower fitting CM
1200	111.688	20.244	0.00	Surface member CM
1300	38.313	-106.846	0.00	Surface member CM
1426	0.0	0.0	254.949	Marker origin, ground
1428	10.0	0.0	244.949	Marker origin, ground
1429	0.0	10.0	244.949	Marker origin, ground
1491	0.0	0.0	244.949	Marker origin, ground
1492	0.0	0.0	244.949	Marker origin, ground
0191	0.0	0.0	244.199	Marker origin, upper fitting
0192	0.0	0.0	244.199	Marker origin, upper fitting

TABLE 8. - TETRAHEDRAL COMPONENT DATA.

Component	Data
Cluster Fittings 01, 05, 08, & 11	Mass = .00259 lb sec^2/in. IP = .01 .01 .005
Diagonal Members 02, 03, & 04	Mass = .004653 IP = 22.596 22.596 .10
Surface Members 06, 07, 09, 10, 12, & 13	Mass = .002819 IP = 5.0762 5.0762 .10

Note: IP = IX IY IZ (lb sec^2 in)

TABLE 9. - COMMAND FILE FOR TETRAHEDRAL TRUSS.

```
TYPE JCATET ACF,1
FORCE/90607,A=10,KT=100,T=0
FORCE/90910,A=10,KT=100,T=0    Resets original input
FORCE/91213,A=10,KT=100,T=0
STA
FORCE/90607,A=45
FORCE/90910,A=45
FORCE/91213,A=45
STA
FORCE/90607,A=90
FORCE/90910,A=90
FORCE/91213,A=90
STA
FORCE/90607,A=135
FORCE/90910,A=135
FORCE/91213,A=135
STA
FORCE/90607,A=179
FORCE/90910,A=179
FORCE/91213,A=170
STA
FORCE/90607,A=0,KT=0.2944,T=-27
FORCE/90910,A=0,KT=0.2944,T=-27    Resets back to original input
FORCE/91213,A=0,KT=0.2944,T=-27
FORCE/1427,KT=0
FORCE/1497,KT=0
FORCE/1498,KT=0
FORCE/90607,LIST
FORCE/90910,LIST
FORCE/91213,LIST
FORCE/1427,LIST
FORCE/1497,LIST
FORCE/1498,LIST
TRAN
3 0,00
STOP
$
```

TABLE 10. - FUNCTION SUBPROGRAM FOR TETRAHEDRAL TRUSS.

```
TYPE JCATET.FOR;9
      FUNCTION FSUB(ID,TIME,APAR,PAR,DFLAQ)
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION APAR(6),PAR(5)
      LOGICAL DFLAG
C
      FSUB=0.0
      IF(TIME.GT.0.0) RETURN
C
      RAD=DSQRT(APAR(1)**2+APAR(2)**2+APAR(3)**2)
      FSUB=PAR(1)*(10.0-RAD)
      RETURN
      END
      FUNCTION TSUB(ID,TIME,PHI,DPHI,PAR,DFLAG)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION PAR(5)
      LOGICAL DFLAG
C
      TSUB=0.D0
C
      IF(TIME.EQ.0.0) RETURN
      ANG=PAR(1)
      IF(PHI.GT.ANG) RETURN
      IF(PHI.LT.0.0) GO TO 100
      TSUB=(ANG-PHI)*(27.0/ANG-PAR(2)*DPHI)
      RETURN
C
  100 C=PAR(2)
      IF(DPHI.GT.0.0)C=C*0.1
      TSUB=27.0-PAR(3)*PHI-C*DPHI
      RETURN
      END
$
```

TABLE 11. - INPUT FILE FOR TETRAHEDRAL TRUSS.

```
TETRAHEDRAL TRUSS UNIT
LIST


PART/01 ,MASS- 00259 ,IP- 01 , 01 , 005 ,CM-0100
MARKER/0100 ,OP-0 0 ,0 0 ,244 199
MA/0191 ,OP-0 ,0 ,244 199 ,ZP-1 ,0 ,244 199
MA/0192 ,OP-0 ,0 ,244 199 ,ZP-0 ,1 ,244 199

MARKER/0101 ,OP-0 0 ,-1 25 ,243 179 ,EU-90 ,90 ,0
MARKER/0102 ,OP--1 083 ,0 625 ,243 179 ,EU-150 ,90 ,0
MARKER/0103 ,OP-1 083 ,0 625 ,243 179 ,EU-30 ,90 ,0
MARKER/0116 ,OP-0 0 ,0 0 ,244 949
MARKER/0117 ,OP-0 0 ,0 0 ,243 179 ,EU-30 ,0 ,0

PART/02 ,MASS- 004653 ,IP-22 596 ,22 596 , 1 ,CM-0200
MARKER/0200 ,OP--75 00 ,43 302 ,124 975 ,EU-60 ,35 26 ,0 0
MARKER/0202 ,OP--1 083 ,0 625 ,243 179 ,EU-150 ,90 ,0
MARKER/0205 ,OP--148 917 ,85 978 ,1 77 ,EU-150 ,90 ,0

PART/03 ,MASS- 004653 ,IP-22 596 ,22 596 , 1 ,CM-0300
MARKER/0300 ,OP-75 00 ,43 302 ,124 975 ,EU-120 ,-35 26 ,0
MARKER/0303 ,OP-1 083 ,0 625 ,243 179 ,EU-30 ,90 ,0
MARKER/0309 ,OP-148 917 ,85 978 ,1 77 ,EU-30 ,90 ,0

PART/04 ,MASS- 004653 ,IP-22 596 ,22 596 , 1 ,CM-0400
MARKER/0400 ,OP-0 0 ,-86 603 ,124 975 ,EU-0 ,-35.26 ,0
MARKER/0401 ,OP-0 0 ,-1 25 ,243 179 ,EU-90 ,90 ,0
MARKER/0413 ,OP-0 0 ,-171.955 ,1.77 ,EU-90 ,90 ,0

PART/05 ,MASS- 00259 ,IP- 01 , 01 , 005 ,CM-0500
MARKER/0500 ,OP-0 0 ,-173 205 ,0.75
MARKER/0513 ,OP-0 0 ,-171 955 ,1 77 ,EU-90 ,90 ,0
MARKER/0514 ,OP--1 625 ,-170 390 ,0 00 ,EU-120 ,90 ,0
MARKER/0512 ,OP-1 625 ,-170 390 ,0 0 ,EU-60 ,90 ,0
MARKER/0520 ,OP-0 0 ,-173.205 ,0.0

PART/06 ,MASS- 002819 ,IP-5 0762 ,5 0762 ,.1 ,CM-0600
MARKER/0600 ,OP--38 313 ,-106 846 ,0 00 ,EU-30 ,90 ,0
MARKER/0614 ,OP--1 625 ,-170 390 ,0 0 ,EU-120 ,90 ,0
MARKER/0615 ,OP--75 00 ,-43.301 ,0 00 ,EU-120 ,90 ,0
MARKER/0615 ,OP--75.00 ,-43.301 ,0.00 ,EU-120 ,90 ,0

PART/07 ,MASS- 002820 ,IP-5 0762 ,5 0762 , 1 ,CM-0700
MARKER/0715 ,OP--75 00 ,-43 301 ,0 00 ,EU-120 ,90 ,0
MARKER/0700 ,OP--111 688 ,28 244 ,0 00 ,EU-30 ,90 ,0
MARKER/0704 ,OP--148.375 ,83.788 ,0 0 ,EU-120 ,90 ,0
```

TABLE 11. - (Cont.)

```
PART/08,MASS- 00259,IP- 01, 01, 005,CM-0800
MARKER/0820,QP--150 ,86 603,0 75
MARKER/0804,QP--148 375,83 788,0 0,EU-120,90,0
MARKER/0805,QP--148 917,85 978,1 77,EU-150,90,0
MARKER/0806,QP--146 750,86 603,0 0,EU-0,90,0
MARKER/0818,QP--150 ,86 603,0 0

PART/09,MASS- 002829,IP-5 0762,5 0762, 1,CM-0900
MARKER/0900,QP--73 375,86 603,0 00,EU-90,90,0
MARKER/0906,QP--146 750,86 603,0 0,EU-0,90,0
MARKER/0907,QP-0 00,86 603,0 00,EU-0,90,0
MARKER/9907,QP-0 00,86 603,0 00,EU-0,90,0

PART/10,MASS- 002829,IP-5 0762,5 0762, 1,CM-1000
MARKER/1000,QP-73 375,86 603,0 00,EU-90,90,0
MARKER/1007,QP-0 0,86 603,0 00,EU-0,90,0
MARKER/1008,QP-146 750,86 603,0 0,EU-0,90,0

PART/11,MASS- 00259,IP- 01, 01, 005,CM-1100
MARKER/1100,QP-150 00,86 603,0 75
MARKER/1108,QP-146 750,86 603,0 00,EU-0,90,0
MARKER/1109,QP-148 917,85 978,1 77,EU-30,90,0
MARKER/1110,QP-148 375,83 788,0 0,EU-60,90,0
MARKER/1119,QP-150 00,86 603,0 0

PART/12,MASS- 002829,IP-5 0762,5 0762, 1,CM-1200
MARKER/1200,QP-111 688,20 244,0 00,EU-150,90,0
MARKER/1210,QP-148 375,83 788,0 0,EU-60,90,0
MARKER/1211,QP-75 00,-43 301,0 00,EU-240,90,0

MARKER/1291,QP-75 00,-43 301,0.00,EU-240,90,0


PART/13,MASS- 002829,IP-5 0762,5 0762, 1,CM-1300
MARKER/1300,QP-38 313,-106 846,0 00,EU-150,90,0
MARKER/1311,QP-75 00,-43 301,0 00,EU-240,90,0

MARKER/1312,QP-1 625,-170.390,0 0,EU-60,90,0


PART/14,GROUND
MARKER/1410,QP-0 0,0 0,244 949
MA/1491,QP-0,0,244 949,ZP-1,0,244.949
MA/1492,QP-0,0,244 949,ZP-0,1,244.949

MARKER/1418,QP--150 00,86 603,0 0
MARKER/1419,QP-150 00,86 603,0 0
MARKER/1420,QP-0 0,-173 205,0 0

MARKER/1426,QP-0 0,0 0,254 949
MARKER/1428,QP-10,0,244 949
MARKER/1429,QP-0,10,244.949
```

TABLE 11. - (Cont.)

```
FORCE/1426,FINPUT,I-0100,J-1426,PAR-100
FORCE/1428,FINPUT,I-0100,J-1428,PAR-100
FORCE/1429,FINPUT,I-0100,J-1429,PAR-100

FORCE/1427,GTORQUE,I-0100,J-1426,KT-1000
FORCE/1497,GTORQUE,I-0101,J-1491,KT-1000
FORCE/1498,GTORQUE,I-0102,J-1492,KT-1000
```

Active only during execution for static equilibrium (STA)

```
        JOINTS
    JO/0104,REV,I-0101,J-0401
FORCE/0104,BUSHING,I-0101,J-0401,K-1 E4,1 E4,1 E4,KT-1 0E4,1 0E4

,C- 2E4, 2E4, 2E4,CT-0 2E4,0 2E4,0

    JO/0102,REV,I-0102,J-0202
FORCE/0102,BUSHING,I-0102,J-0202,K-1 E4,1 E4,1 E4,KT-1 0E4,1 0E4

,C- 2E4, 2E4, 2E4,CT-0 2E4,0 2E4,0

    JO/0103,REV,I-0103,J-0303
FORCE/0103,BUSHING,I-0103,J-0303,K-1 E4,1 E4,1 E4,KT-1 0E4,1 0E4

,C- 2E4, 2E4, 2E4,CT-0 2E4,0 2E4,0

JO/0504,REV,I-0413,J-0513

    JO/0506,REV,I-0514,J-0614
FORCE/0506,BUSHING,I-0514,J-0614,K-1 E4,1 E4,1 E4,KT-1 0E4,1 0E4

,C- 2E4, 2E4, 2E4,CT-0 2E4,0 2E4,0

JO/0513,REV,I-0512,J-1312
JO/0802,REV,I-0805,J-0205
JO/0807,REV,I-0804,J-0704
JO/0809,REV,I-0806,J-0906
JO/1103,REV,I-1109,J-0309
JO/1110,REV,I-1108,J-1008
JO/1112,REV,I-1110,J-1210
JO/0607,REV,I-0615,J-0715
JO/0910,REV,I-0907,J-1007
JO/1213,REV,I-1211,J-1311

       GENERATORS

    GEN/0607,CON,JOINT-0607,PAR-1 0,0 0
FORCE/03607,GTORQUE,I-615,J-715,KT-0.2944,T--27

FORCE/02607,TINPUT,I-0615,J-715,PAR-100,1000,1000
REQ/8886,FORCE,I-0615,J-715,RM-715        10D

    GEN/0910,CON,JOINT-0910,PAR-1.0,0 0
FORCE/03910,GTORQUE,I-907,J-1007,KT-0.2944,T--27
```

TABLE 11. - (Cont.)

10 Deg.

```
FORCE/83910 ,TINPUT ,I-9937 ,J-1037 ,PAR-100 ,1000 ,1000
REQ/8887 ,FORCE ,I-9907 ,J-1007 ,RM-1007

     CEN/1213 ,CON ,JOINT-1213 ,PAR-1 0 ,8 0
FORCE/91213 ,CTORQUE ,I-1211 ,J-1311 ,KT-0 2944 ,T--27

FORCE/81213 ,TINPUT ,I-1291 ,J-1311 ,PAR-100 ,1000 ,1000
REQ/8988 ,FORCE ,I-1291 ,J-1311 ,RM-1311


      SENSOR/811 ,DISP ,I-0018 ,J-1119 ,X ,VALUE ,300 ,PRINT
       ,HALT ,EQ ,ERROR- 10

                GRAPHICS
GR/1 ,OUT-0906 ,0907
GR/2 ,OUT-1007 ,1008
GR/3 ,OUT-1210 ,1211
GR/4 ,OUT-1311 ,1312
GR/5 ,OUT-0614 ,0615
GR/6 ,OUT-0715 ,0704
GR/7 ,OUT-0205 ,0202
GR/8 ,OUT-0309 ,0303
GR/9 ,OUT-0401 ,0413
GR/10 ,CIR ,CM-0117 ,R-1 25 ,SEG-3
GR/11 ,CIR ,CM-0520 ,R-3 25 ,SEG-6
GR/12 ,OUT-0512 ,0520
GR/13 ,OUT-0514 ,0520
GR/14 ,OUT-0520 ,0513
GR/15 ,CIR ,CM-0818 ,R-3 25 ,SEG-6
GR/16 ,OUT-0806 ,0818
GR/17 ,OUT-0804 ,0818
GR/18 ,OUT-0818 ,0805
GR/19 ,CIR ,CM-1119 ,R-3 25 ,SEG-6
GR/20 ,OUT-1109 ,1119
GR/21 ,OUT-1110 ,1119
GR/22 ,OUT-1110 ,1109

               OUTPUT

REQ/0104 ,F ,0101 ,0401 ,RM-101
REQ/0102 ,F ,0102 ,0202 ,RM-102
REQ/0103 ,F ,0103 ,0303 ,RM-103
REQ/0504 ,F ,I-0413 ,J-0513 ,RM-413
REQ/0506 ,FORCE ,I-0514 ,J-0814 ,RM-514
REQ/0513 ,FORCE ,I-0512 ,J-1312 ,RM-512
REQ/0802 ,FORCE ,I-0805 ,J-0205 ,RM-805
REQ/0807 ,FORCE ,I-0804 ,J-0704 ,RM-804
REQ/0809 ,FORCE ,I-0806 ,J-0906 ,RM-806
REQ/1103 ,FORCE ,I-1109 ,J-0309 ,RM-1109
REQ/1110 ,FORCE ,I-1108 ,J-1008 ,RM-1108
REQ/1110 ,FORCE ,I-1108 ,J-1008 ,RM-1108
REQ/1112 ,FORCE ,I-1110 ,J-1210 ,RM-1110
REQ/0607 ,FORCE ,I-0615 ,J-0715 ,RM-615
REQ/0910 ,FORCE ,I-0907 ,J-1007 ,RM-907
REQ/1213 ,FORCE ,I-1211 ,J-1311 ,RM-1211

REQ/9991 ,DISP ,0101 ,0401 ,RM-101
REQ/9992 ,DISP ,0102 ,0202 ,RM-102
REQ/9993 ,DISP ,0103 ,0303 ,RM-103
REQ/9994 ,DISP ,I-0413 ,J-0513 ,RM-413
REQ/9995 ,DISP ,I-0514 ,J-0814 ,RM-514
REQ/9996 ,DISP ,I-0512 ,J-1312 ,RM-512
REQ/9997 ,DISP ,I-0805 ,J-0205 ,RM-805
REQ/9998 ,DISP ,I-0804 ,J-0704 ,RM-804
REQ/9999 ,DISP ,I-0806 ,J-0906 ,RM-806
REQ/9981 ,DISP ,I-1109 ,J-0309 ,RM-1109
REQ/9982 ,DISP ,I-1108 ,J-1008 ,RM-1108
REQ/9983 ,DISP ,I-1110 ,J-1210 ,RM-1110
REQ/9984 ,DISP ,I-0615 ,J-0715 ,RM-615
REQ/9985 ,DISP ,I-0907 ,J-1007 ,RM-907
REQ/9986 ,DISP ,I-1211 ,J-1311 ,RM-1211

              SYSTEM CARDS
SYS/GC-1 0 ,IGRAV-0 ,JGRAV-0 ,KGRAV-0 ,MAXIT-50
 ,EPRINT ,            ,DUMP ,EPRINT ,REQDUMP ,RHSDUMP


              OUTPUT CARDS
OUTPUT/SAVEREQ ,GRSAVE ,END-10. ,YPR
END
```

TABLE 12. - OUTPUT FOR TETRAHEDRAL TRUSS, REQUEST NO. 9999.

TETRAHEDRAL TRUSS UNIT
REQUEST NUMBER 9999

DISPLACEMENT OF MARKER 806 RELATIVE TO MARKER 906
EXPRESSED IN THE COORDINATE SYSTEM OF MARKER 806

TIME	MAC	X	Y	Z	YAW	PITCH	ROLL
0 0000	0 000	0 000	0 000	0 000	-89 501	0 000	0 000
0 0333	0 000	0 000	0 000	0 000	-89 518	0 000	0 000
0 0667	0 000	0 000	0 000	0 000	-89 570	0 000	0 000
0 1000	0 000	0 000	0 000	0 000	-89 656	0 000	0 000
0 1333	0 000	0 000	0 000	0 000	-89 773	0 000	0 000
0 1667	0 000	0 000	0 000	0 000	-89 900	0 000	0 000
0 2000	0 000	0.000	0 000	0 000	-89 990	0 000	0 000
0 2333	0 000	0 000	0 000	0 000	-89 951	0 000	0 000
0 2667	0 000	0 000	0 000	0 000	-89 677	0 000	0 000
0 3000	0 000	0 000	0 000	0 000	-89 122	0 000	0 000
0 3333	0 000	0.000	0 000	0 000	-88 342	0 000	0.000
1 6333	0 000	0 000	0 000	0 000	-10 087	0 000	0 000
1 6667	0 000	0 000	0 000	0 000	-2 598	0 000	0 000
1 7000	0 000	0 000	0 000	0 000	0 541	0 000	0 000
1 7333	0 000	0 000	0 000	0 000	0 132	0 000	0 000
1 7667	0 000	0 000	0 000	0 000	-0 747	0 000	0 000
1 8000	0 000	0 000	0 000	0 000	-0 656	0 000	0 000
1 8333	0 000	0 000	0 000	0 000	-0 651	0 000	0 000

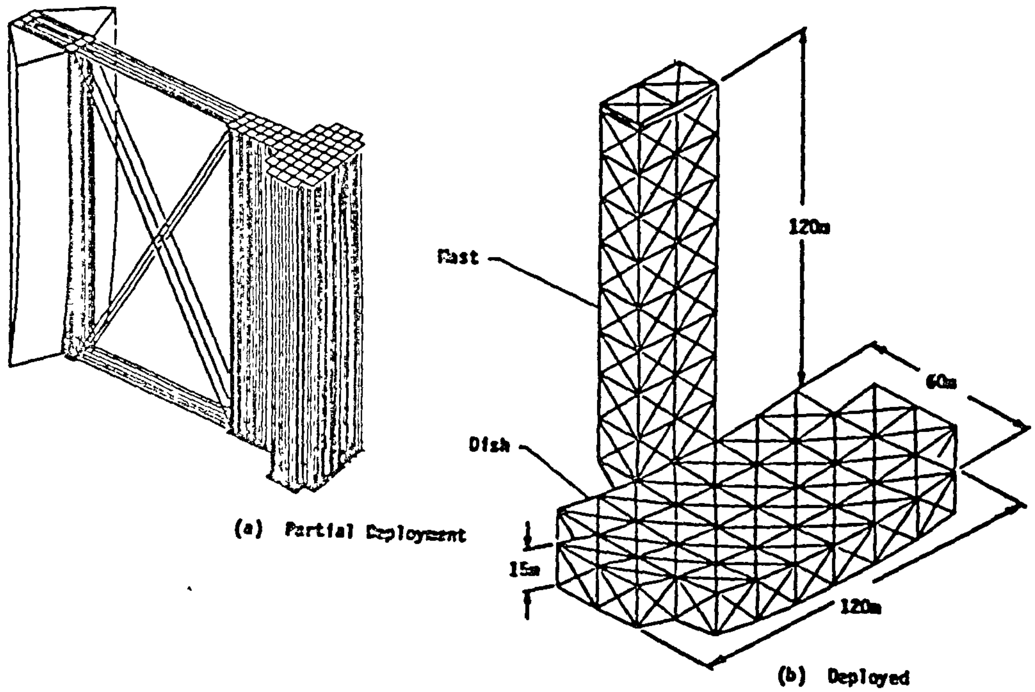

Figure 1. - Box Truss Antenna

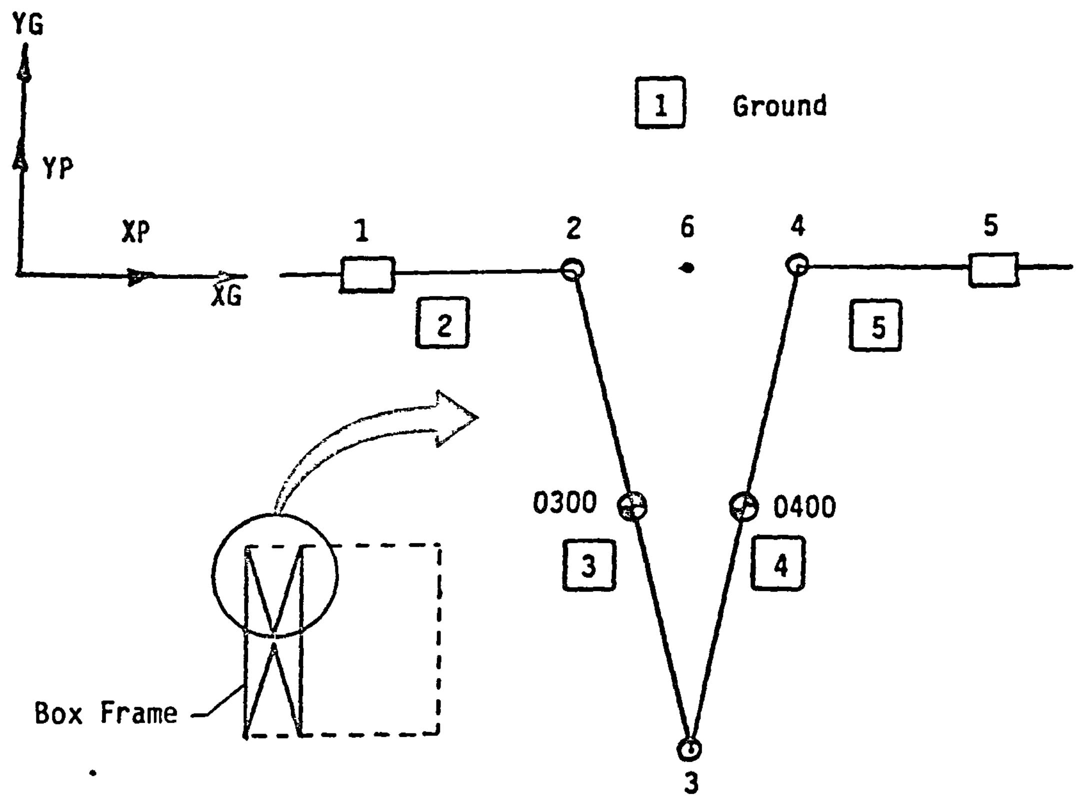

Figure 2. - Box Truss Surface Member Model

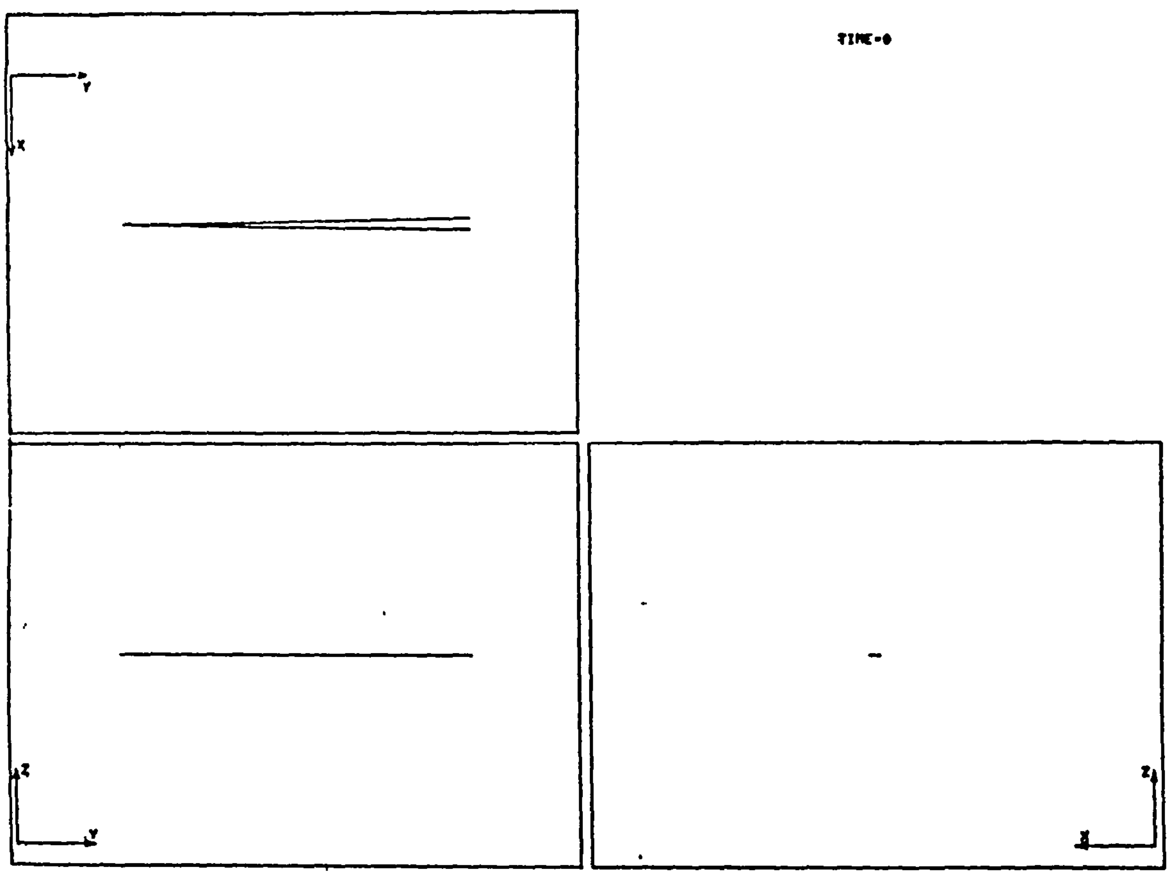

Figure 3. - Box Truss Surface Member, Time = 0. seconds

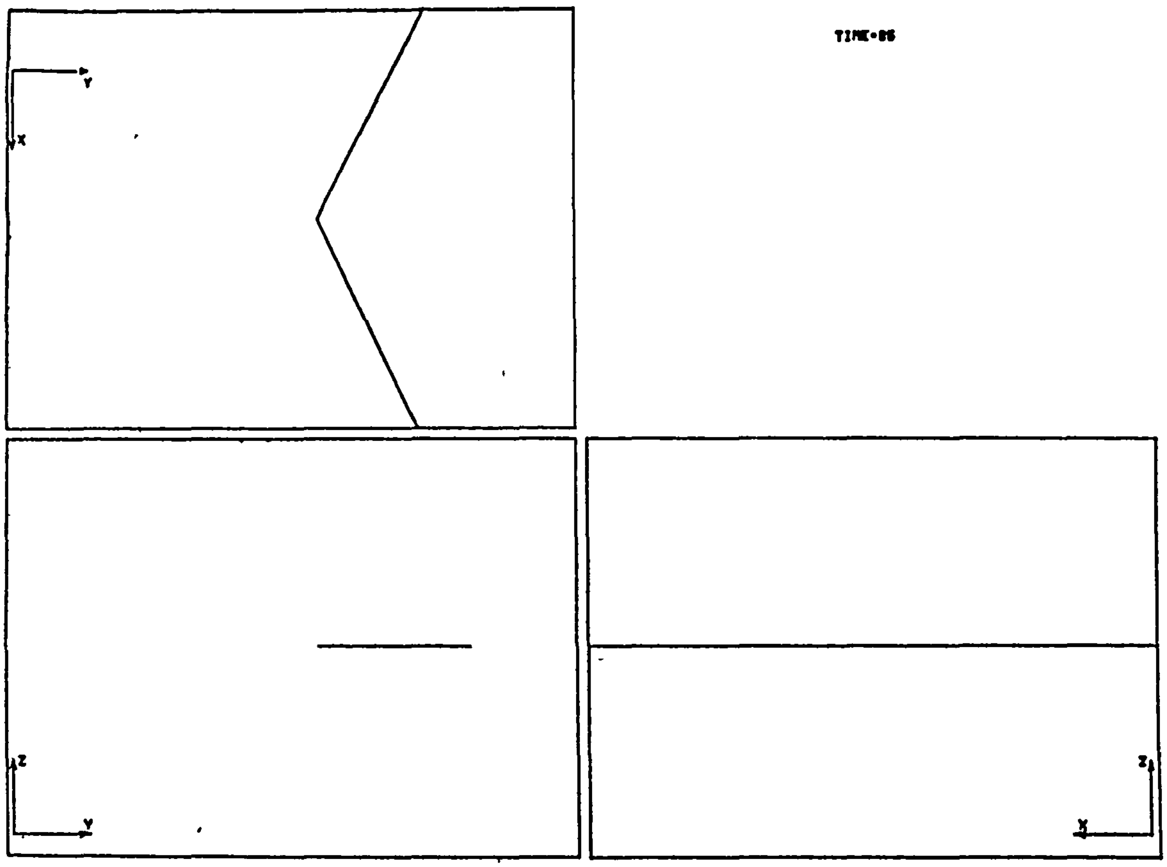

Figure 4. - Box Truss Surface Member, Time = 85 seconds

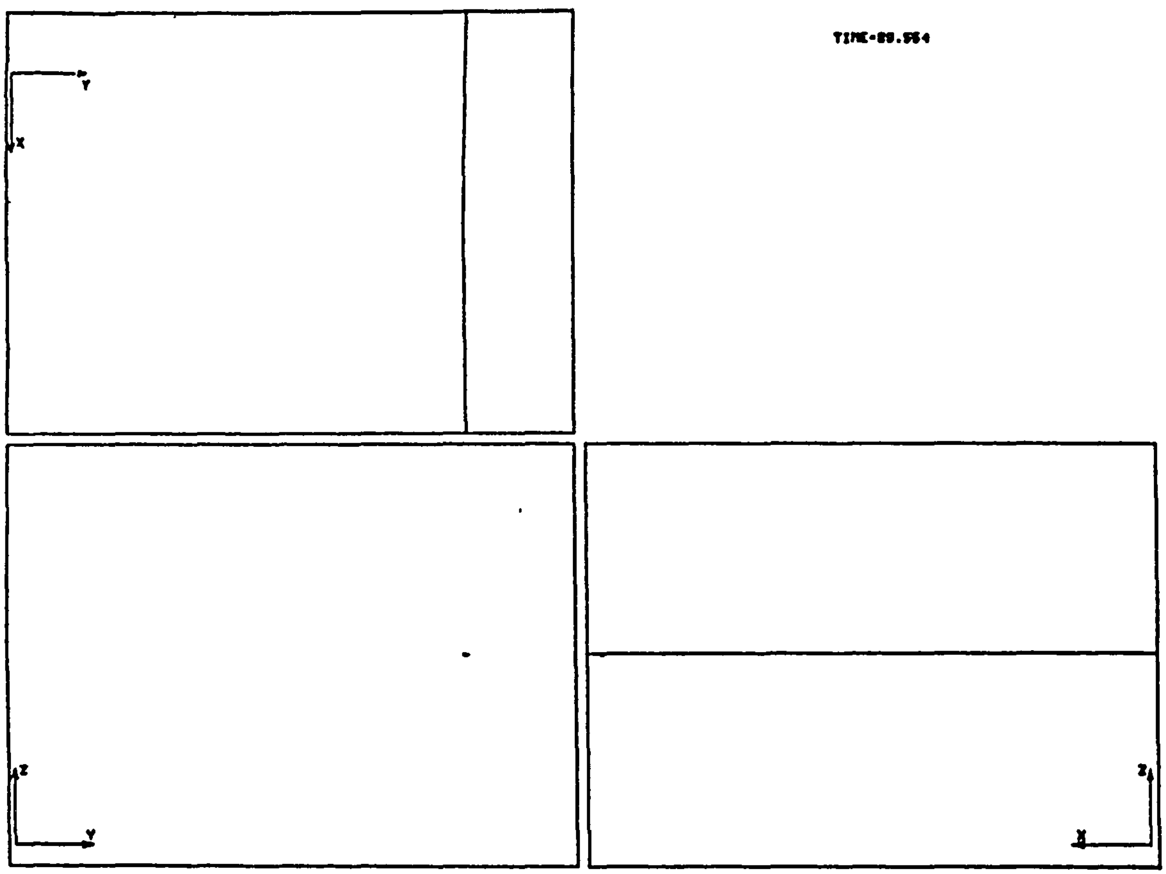

Figure 5. - Box Truss Surface Member, Time = 89.55 seconds

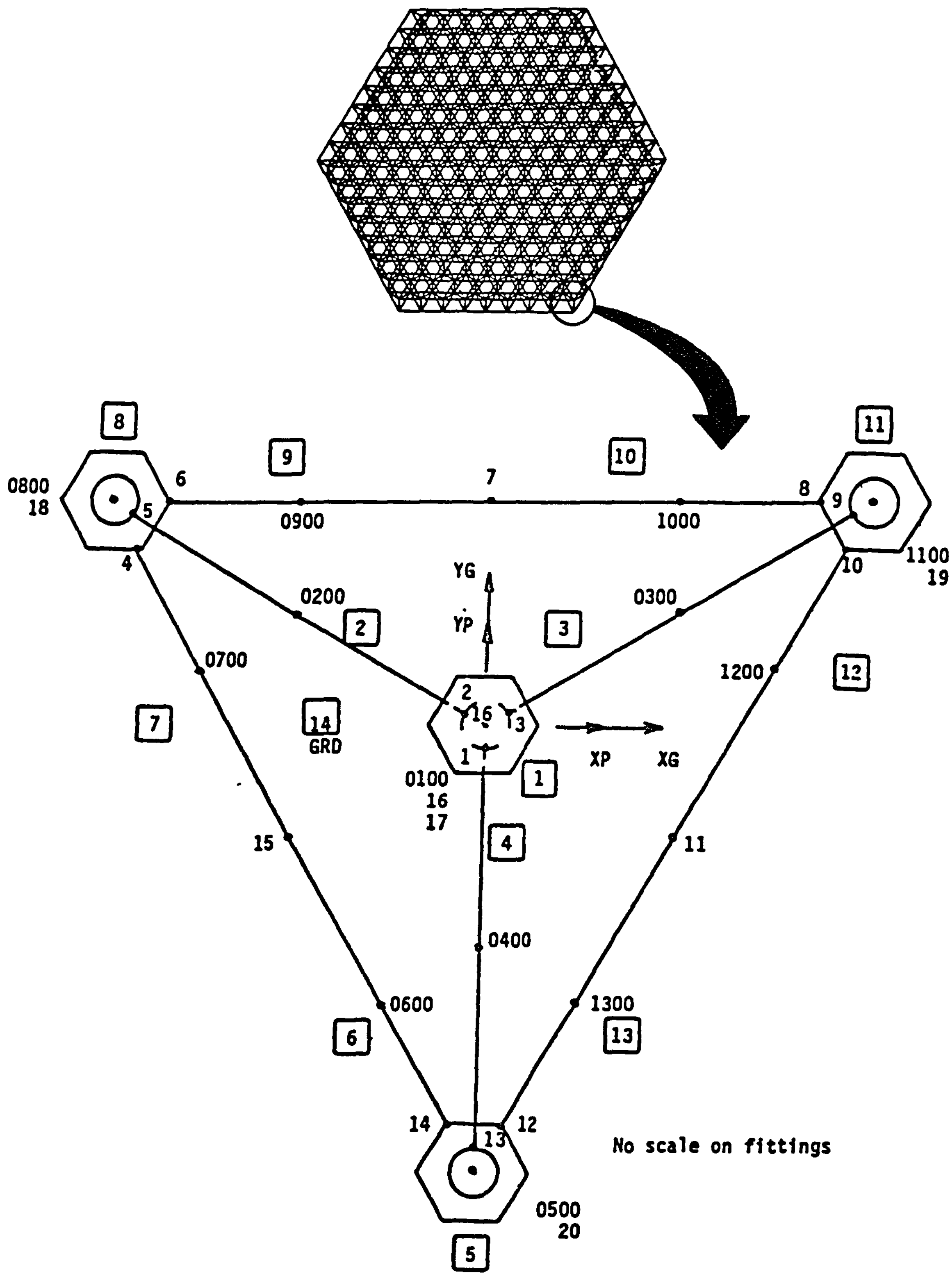

Figure 6. - Tetrahedral Truss Model

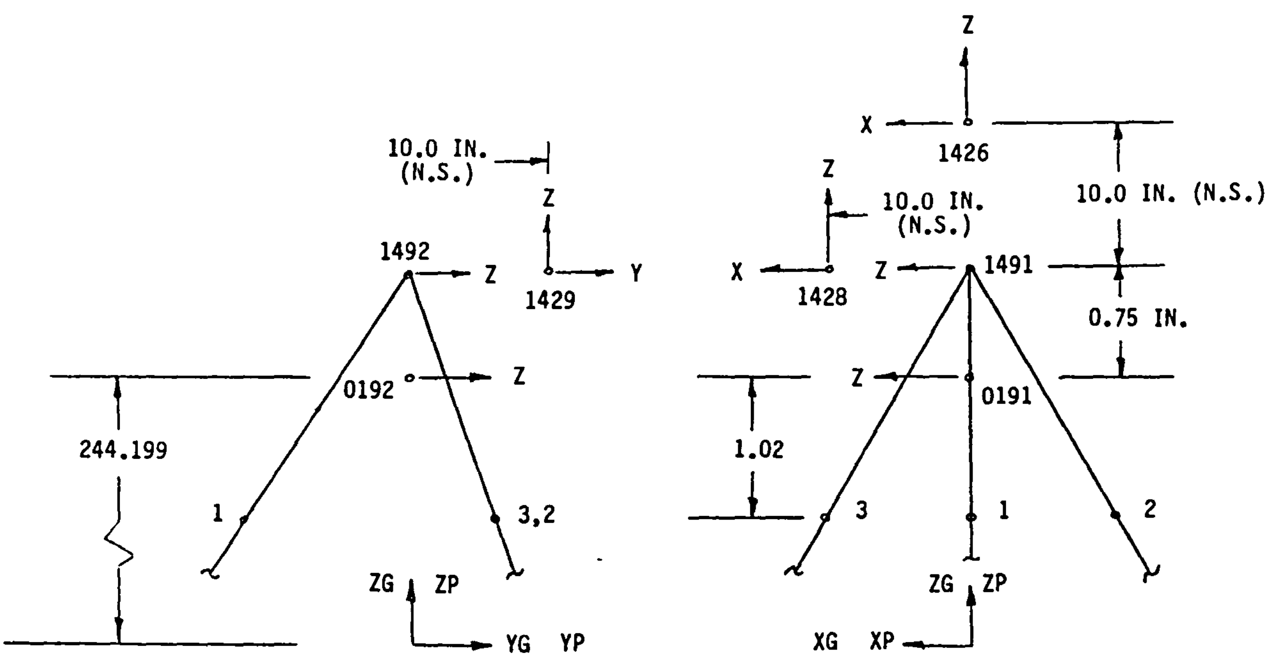

Figure 7. - Marker Locations for Retraction from Open to Closed Position.

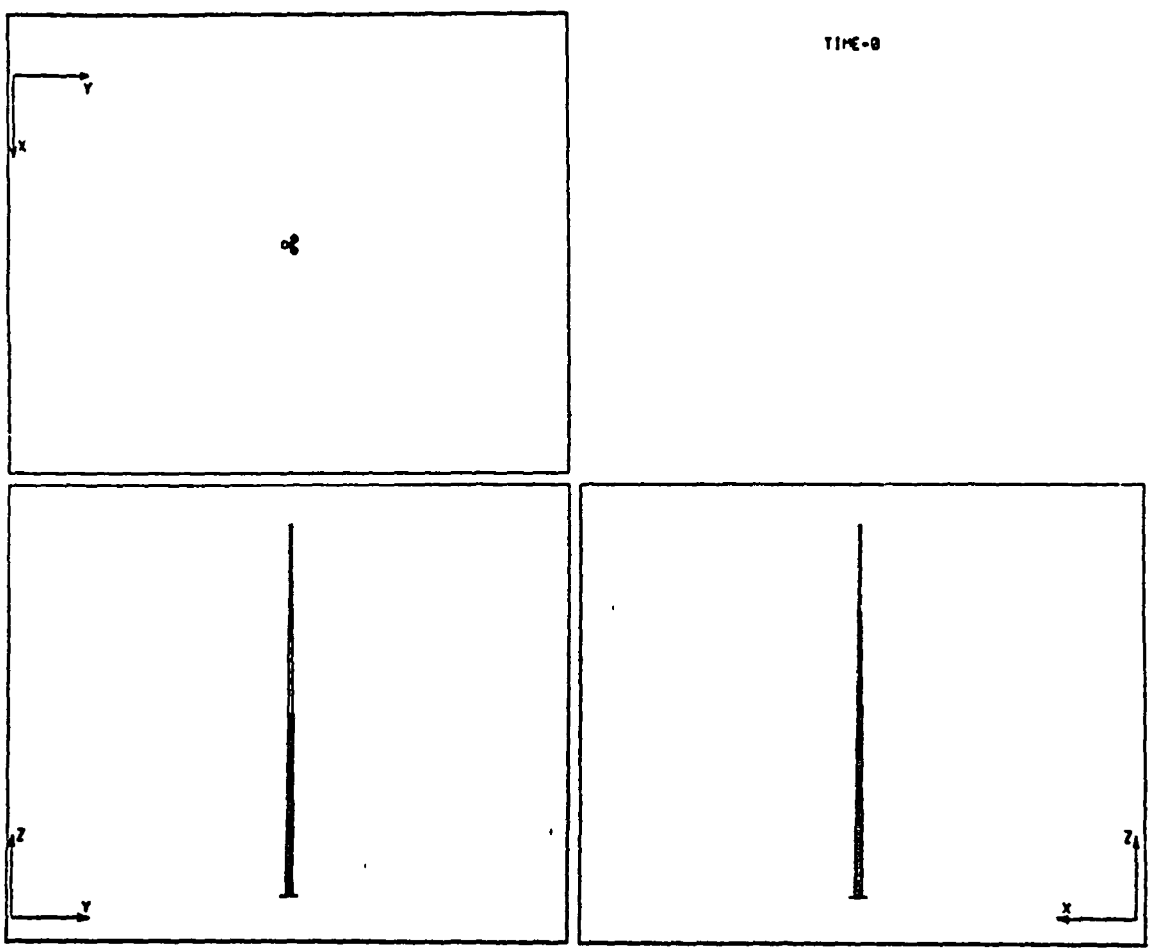

Figure 8. - Tetrahedral Truss, Time = 0. seconds

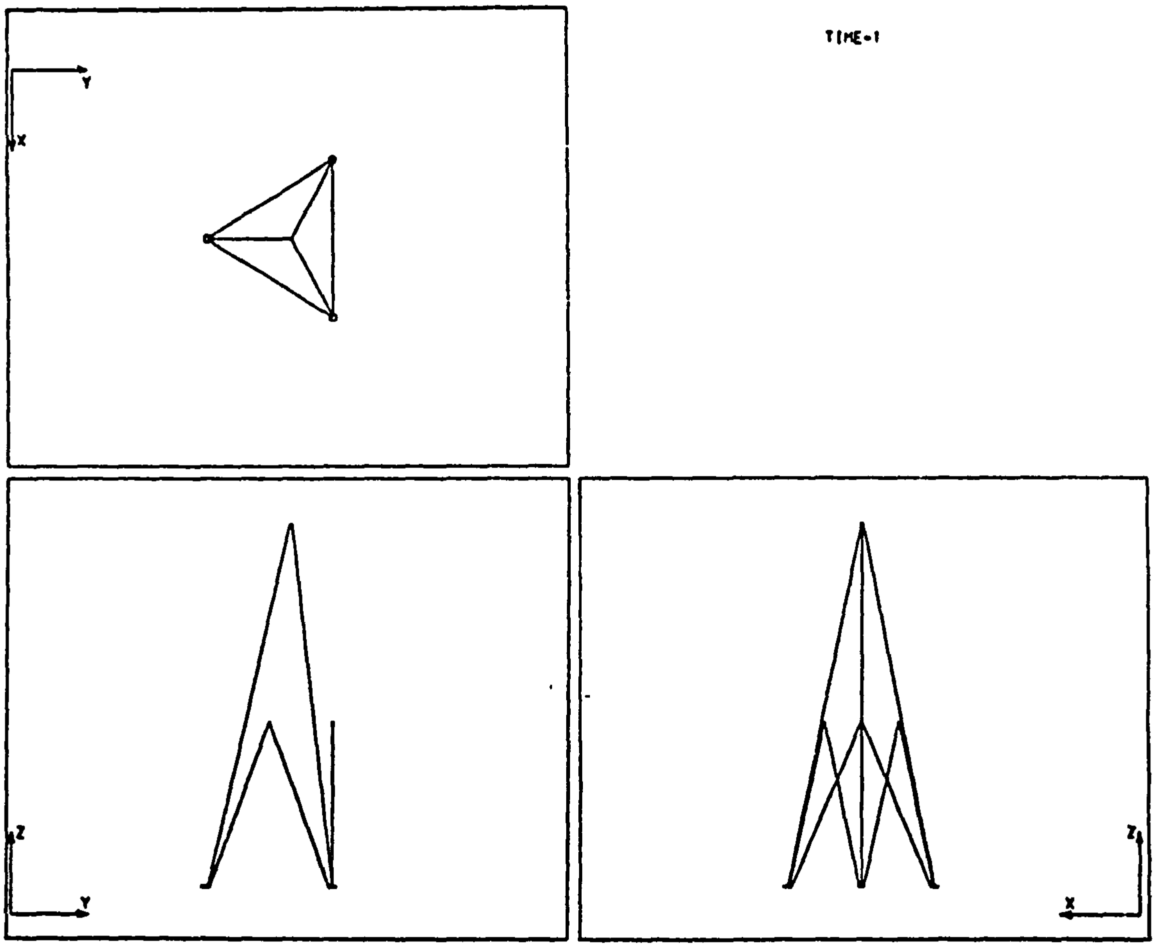

Figure 9. - Tetrahedral Truss, Time = 1.0 seconds

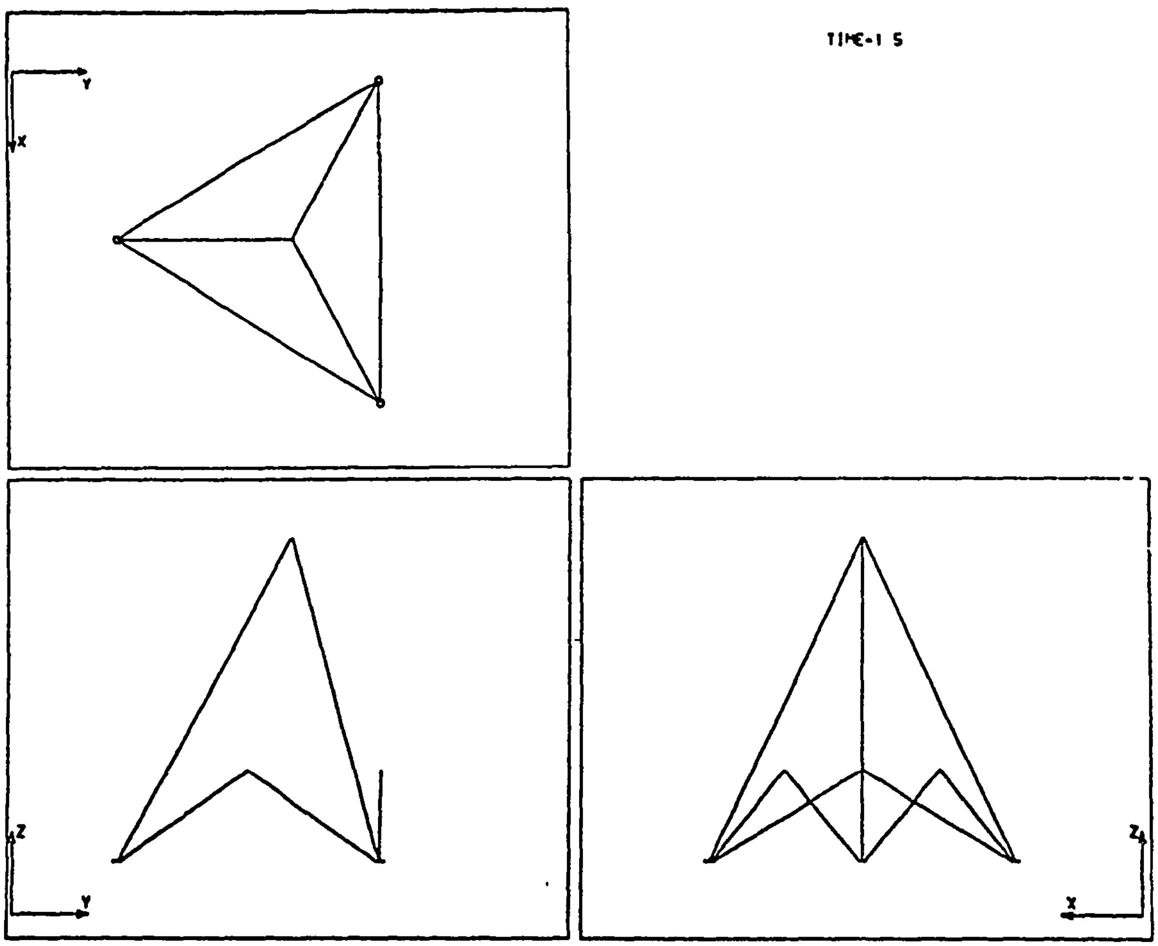

Figure 10. - Tetrahedral Truss, Time = 1.5 seconds

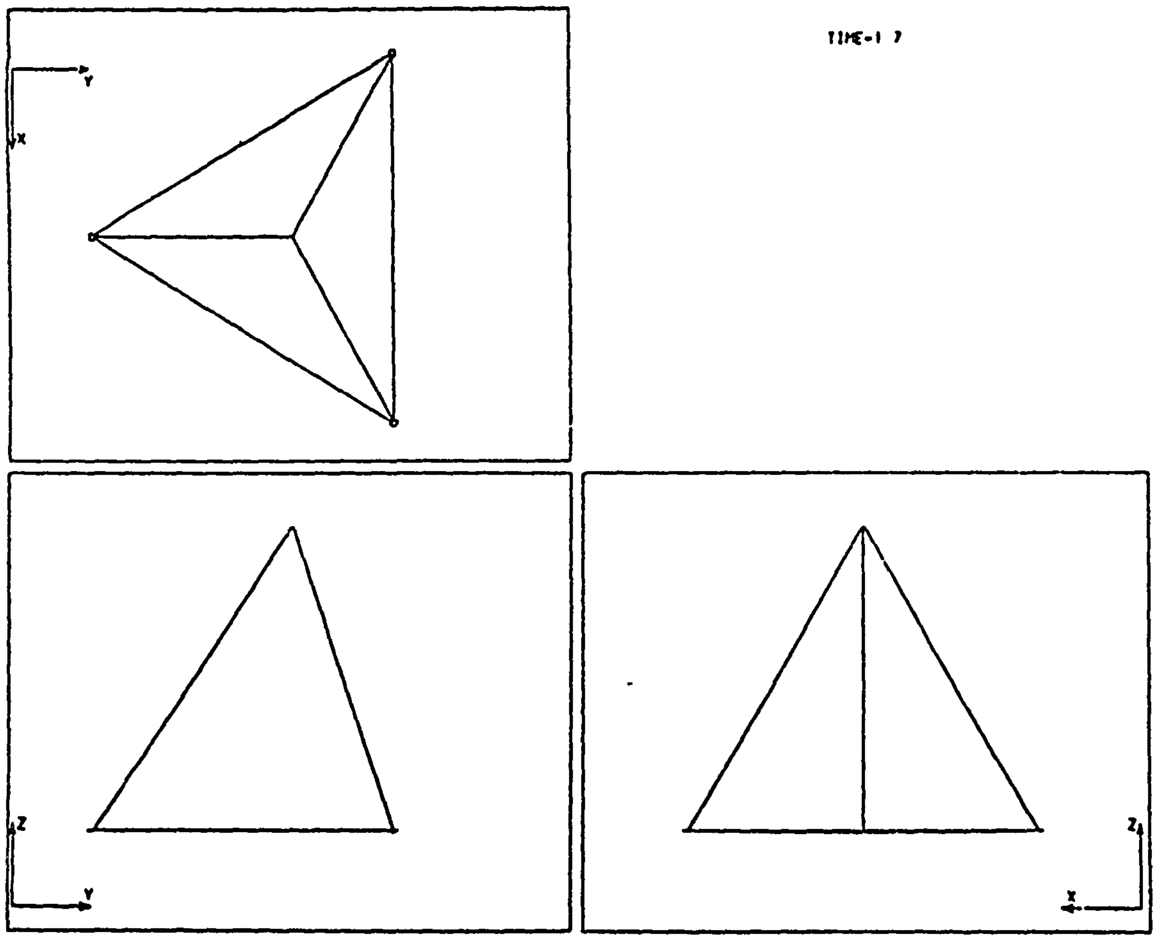

Figure 11. - Tetrahedral Truss, Time = 1.7 seconds

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA CR-177927		

4 Title and Subtitle	5 Report Date
APPLICATION OF THE ADAMS PROGRAM TO DEPLOYABLE SPACE TRUSS STRUCTURES	JULY 1985
	6 Performing Organization Code
7 Author(s)	8 Performing Organization Report No
R. E. CALLESON	
	10 Work Unit No
9 Performing Organization Name and Address	
Kentron International, Inc. 3221 N. Armistead Avenue Hampton, VA 23666	11 Contract or Grant No NAS1-18000
	13 Type of Report and Period Covered Contractor Report
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14 Sponsoring Agency Code 506-62-23

15 Supplementary Notes

Langley Technical Monitor - J. W. Goslee

16 Abstract

The need for a computer program to perform kinematic and dynamic analyses of large truss structures while deploying from a packaged configuration in space led to the evaluation of several existing programs. ADAMS (Automatic Dynamic Analysis of Mechanical Systems), a generalized program for performing the dynamic simulation of mechanical systems undergoing large displacements, is applied to two concepts of deployable space antenna units. One concept is a one-cube folding unit of Martin Marietta's Box Truss Antenna and the other is a tetrahedral truss unit of a Tetrahedral Truss Antenna. Adequate evaluation of dynamic forces during member latch-up into the deployed configuration is not yet available from the present version of ADAMS since it is limited to the assembly of rigid bodies. Included is a method for estimating the maximum bending stress in a surface member at latch-up. Results include member displacement and velocity responses during extension and an example of member bending stresses at latch-up.

17. Key Words (Suggested by Author(s))	18 Distribution Statement
Deployable Space Antennas Kinematics Dynamic Simulation Latch-up Stresses	Unclassified - Unlimited Subject Category 39

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price*
Unclassified	Unclassified	42	A03

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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