INTEGRATED THERMAL-STRUCTURAL ANALYSIS OF LARGE SPACE STRUCTURES

Jack Mahaney, Earl A. Thornton, and Pramote Dechaumphai
Old Dominion University
Norfolk, Virginia 23508

INTRODUCTION

The flight of Columbia marks the advent of large space structures. Soon orbiting structures as much as 1000 meters across may be deployed or constructed in orbit. Many of these structures may be antennas built of a lattice-work of graphite/epoxy truss members.

Optimum antenna performance requires very fine control of the shape of the antenna surface since the shape affects both frequency control and pointing accuracy. A significant factor affecting the antenna shape is the temperature of the structure and the resulting deformation. To accurately predict the temperature of the structure, it is necessary first to accurately predict thermal loads. As the structure orbits the Earth, the thermal loads change constantly so that the thermal-structural response varies continuously throughout the orbit.

The purpose of this paper is to present the results from recent applications of integrated finite-element methodology to heat-load determination and thermal-structural analysis of large space structures (fig. 1).

The paper will concentrate on four areas: (1) the characteristics of the integrated finite element methodology, (2) fundamentals of orbital heat-load calculation, (3) description and comparison of some radiation finite elements, and (4) application of the integrated finite-element approach to the thermal-structural analysis of an orbiting truss structure.

- MOTIVATION
  - SIZE OF STRUCTURES
  - ACCURATE PREDICTION OF HEAT LOADS AND TEMPERATURE
  - CONTROL OF DEFORMATION
- PURPOSE
  - DESCRIBE AN INTEGRATED FINITE ELEMENT (FE) APPROACH FOR THERMAL-STRUCTURAL ANALYSIS OF LARGE SPACE STRUCTURES
- SCOPE
  - CHARACTERISTICS OF INTEGRATED APPROACH
  - FUNDAMENTALS OF IN-ORBIT HEATING
  - DESCRIPTION AND COMPARISON OF FINITE ELEMENTS
  - ANALYSIS OF STRUCTURE

FIGURE 1

CHARACTERISTICS OF INTEGRATED FINITE ELEMENT ANALYSIS

One approach toward integrated thermal-structural analysis capability is a common methodology in a single program capable of both thermal and structural analysis. This approach, herein called the customary approach, has the disadvantage of inefficient data transfer between thermal and structural analyses because of inherent differences between the thermal and structural models. Another disadvantage of the customary approach is that basic differences between the thermal and structural analysis requirements are not exploited.

To exploit the capabilities of the finite element (F.E.) method the concept of integrated thermal-structural analysis was proposed in references 1 and 2. An integrated thermal-structural analysis is characterized by: (1) thermal and structural finite elements formulated with a common geometric discretization with elements formulated to suit the needs of their respective analyses, (2) thermal and structural finite elements which are fully compatible, and (3) equivalent thermal forces which are based upon a consistent finite element force vector (fig. 2).

Some of the benefits of the integrated approach are: (1) improved temperature distributions based upon new thermal elements, (2) more efficient analyses because of the elimination of data processing between dissimilar thermal and structural models, and (3) improved accuracy in the structural analysis through consistent incorporation of the improved temperature distributions.

- COMMON FE METHODOLOGY
- GEOMETRIC MODEL WITH COMMON DISCRETIZATION
- IMPROVED THERMAL ELEMENTS
- MINIMIZE DATA PROCESSING
- TEMPERATURES INTEGRATED INTO STRUCTURAL ANALYSIS

FIGURE 2

Figure 3 shows schematically the concepts of the customary and integrated approaches applied to an orbiting structure. The sequence followed in the customary approach is shown on the left. First, the heating loads are calculated for an appropriate mathematical model. Next, a thermal analysis is performed based upon a thermal model selected to best represent the heat transfer problem. The thermal model may be based on the lumped parameter or F.E. method. Next the nodal temperature data are transferred to the structural analysis. In most cases these data must be processed to conform the input temperature vector to that required by the structural model. Often the structural and thermal models use different nodes and elements, and approximate thermal forces are computed from average element temperatures.

An integrated analysis is shown on the right side of the figure. The heating loads, thermal, and structural analyses are performed on a model based on a common discretization. Although the discretization is common, the thermal and structural elements are formulated to best suit their respective analyses. The transfer of data is compatible, with no data processing required. Consistent thermal forces are computed from thermal element and nodal input data supplied directly from the thermal analysis.

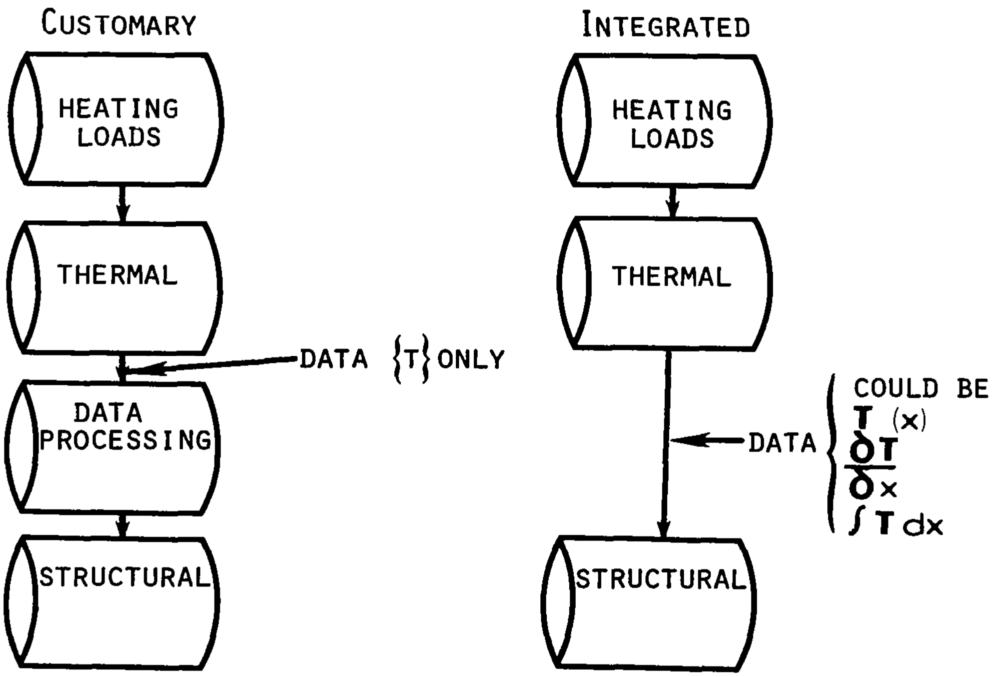


FIGURE 3

ORBITAL HEATING RATE GEOMETRY AND SOURCES

A surface in Earth orbit is heated by both the Sun and the Earth. The solar flux is approximately 1390 W/m^2, but the amount of heat absorbed is a function of the surface absorptivity, a_s, and the projected surface area normal to the flux. Thus, the total solar heating is

$$\dot{q}_s = 1390(W/m^2)\ a_s\ \cos\psi \tag{1}$$

The Earth provides two sources of heat, emission and albedo (fig. 4). The emitted heating is computed by assuming the Earth to be a black body radiating at T = 289 K. The heat absorbed by a surface is a function of the surface absorptivity, a_e, and the view factor F. The view factor between an orbiting flat plate and a sphere was developed by Cunningham (ref. 3) and takes into account the altitude of the surface, size of the sphere, attitude ϕ, and other basic geometric quantities. The amount of heat absorbed by the surface from Earth emission is given by

$$\dot{q}_e = \sigma\ T^4\ a_e\ F \tag{2}$$

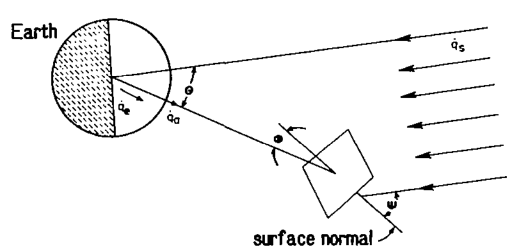
where σ is the Stefan-Boltzmann constant.

The Earth acts as a reflector of solar radiation. The albedo factor, AF, is a measure of the fraction of solar energy reflected. It has been shown by Modest (ref. 4) that while the heat is a complicated function of altitude and attitude (θ,ϕ) a good approximation can be obtained by using Cunningham's view factor F in the equation

$$\dot{q}_a = 1390(W/m^2)\ AF\ \cos\theta\ a_s\ F \tag{3}$$

At any point in the orbit, then, the total heat absorbed by the surface is the sum of the three heating rates above, or

$$\dot{q} = \dot{q}_s + \dot{q}_e + \dot{q}_a \tag{4}$$



Heat sources to orbiting structure
solar, $\dot{q}_s$
Earth emission, $\dot{q}_e$
Earth albedo (reflection of solar), $\dot{q}_a$
Heating rate depends on
orbit and orientation (altitude, Θ, Φ, Ψ)
surface absorptivity

FIGURE 4

DEMONSTRATION OF EARTH SHADOW EFFECTS

This picture of Saturn taken by Voyager I shows dramatically the effect of a planetary shadow (fig. 5). Since the thermal load on an Earth-orbiting structure is reduced as much as 95% when in the Earth's shadow, shadow dwell time is critical. The entry and exit times can be calculated from the period of the orbit and the dwell time, which can be calculated from the altitude of the structure and the angle between the structure's orbit and the plane of the ecliptic (ref. 5).

The umbra-penumbra effects are of little consequence for orbiting structures and are ignored. For example, in geosynchronous orbit a 1000 meter platform travels fast enough to transit the penumbra in less than 4 milliseconds. In lower orbits the time is even shorter.

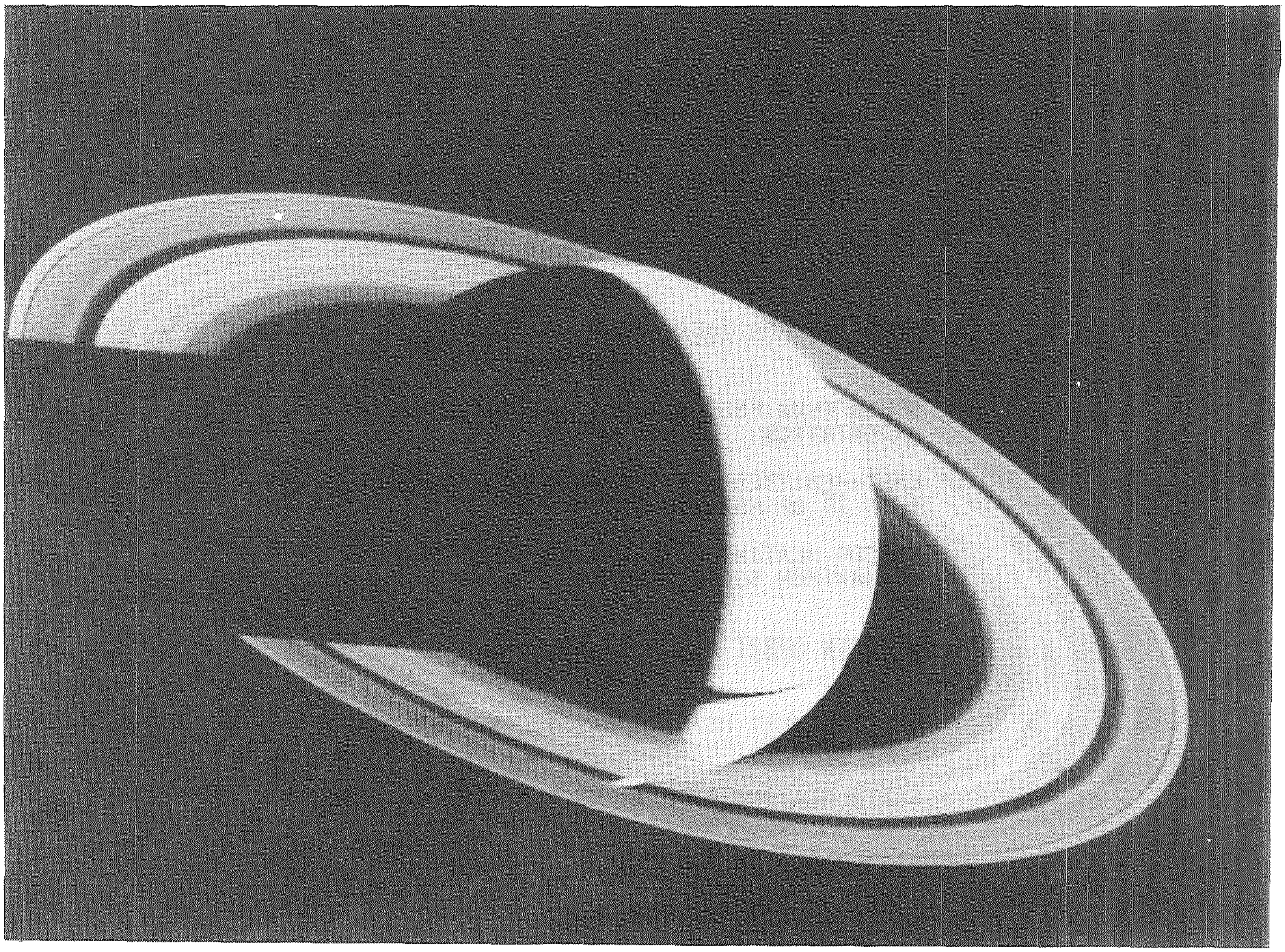


FIGURE 5

ORBITAL HEAT LOADS OF EARTH-FACING SATELLITES

The heating of Earth-facing satellites in geosynchronous and low Earth orbits is considered (fig. 6). A satellite in a geosynchronous Earch orbit (GEO) has a period of 24 hours and an altitude of 35,876 km. In this orbit the effects of solar flux predominate since the structure is so far from the Earth, and they vary as the structure's orientation changes with respect to the Sun. Since the structure is Earth-facing, that is, maintaining a constant orientation with respect to the Earth, the amount of Earth-emitted heating is constant, although very low, less than 1% of the maximum solar heat. Albedo heating varies over the daylight side of the planet (over the night side it is zero), but due to the high altitude is also less than 1% of the maximum solar heating.

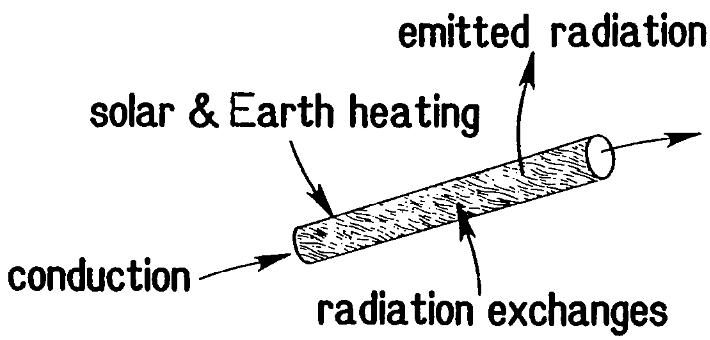
The low Earth orbit (LEO) considered has a period of 90 minutes at an altitude of 279 km, similar to the shuttle orbit. In this orbit all incident heating rates are important. As before, solar and albedo heating vary throughout the orbit while emitted heating is constant. In this LEO, the two Earth heating rates can be as much as 37% of the maximum solar heating.

The effects of transit through the Earth's shadow are significant in any orbit. Within the shadow, the only heating is from Earth-emitted heat. In a GEO, however, this is negligible (less than 15 W/m^2) while in a LEO it is significant. We will see later that the absence of heating during shadow transit can greatly affect the temperature history.

- GEOSYNCHRONOUS (GEO) (PERIOD=24 HOURS, ALTITUDE=35,875 KM)
  - SOLAR FLUX PREDOMINATES AND VARIES WITH ORIENTATION
  - EARTH-EMITTED HEATING RATE CONSTANT, LESS THAN 1% OF MAXIMUM SOLAR FLUX
  - ALBEDO HEATING RATE VARIES, LESS THAN 1% OF MAXIMUM SOLAR FLUX
- LOW EARTH ORBIT (LEO) (PERIOD=90 MINUTES, ALTITUDE=279 KM)
  - ALL INCIDENT HEATING RATES CONSIDERED AND VARY WITH ORIENTATION
  - EARTH HEATING RATE AS MUCH AS 37% OF TOTAL
- EARTH SHADOW SIGNIFICANT
  - EARTH EMITTED HEATING ONLY
  - IN GEO, EARTH EMITTED HEATING ALMOST NEGLIGIBLE
  - IN LEO, EARTH EMITTED HEATING CONSIDERABLE

FIGURE 6

A truss is one of the fundamental structural concepts under consideration for orbiting structures. A typical truss member experiences conduction heat transfer combined with emitted radiation and radiation heating from both nearby truss members and other satellite components (fig. 7). Radiation exchange between members is neglected because computational experience (ref. 6) has shown that the member-to-member radiation heat exchanges in a truss are negligible in comparison with the incident heating and emitted radiation. Although member-to-surface radiation exchanges may be important, they are not considered. In general, both material and surface properties are temperature dependent and vary throughout an orbit. Thus the basic heat transfer problem is inherently nonlinear because of the emitted radiation combined with temperature-dependent properties and transient because of the strong time-dependence of the heat loads. Three alternative F.E. thermal models of a truss member are presented in figure 8.



- Considerations
  - —conduction combined with radiation
  - —nonlinear, transient
  - —member—to—member radiation exchanges
  - —member—to—surface radiation exchanges
  - —temperature dependence of material and surface properties

FIGURE 7

ROD ELEMENT THERMAL MODELS

Three thermal models of a truss member are considered: (1) a conventional two node element with a linear temperature distribution, (2) a nodeless variable higher order element with a quadratic temperature distribution, and (3) an isothermal element. The first two elements are useful in modeling members with significant member temperature gradients due to conduction, and the last element is useful for modeling members with negligible conduction. The isothermal element is similar to traditional lumped heat transfer models and does not transfer heat via conduction between adjacent members as with the first two elements. Thus with isothermal elements the solution of simultaneous equations is avoided, and the transient response of each member is computed separately (fig. 8).

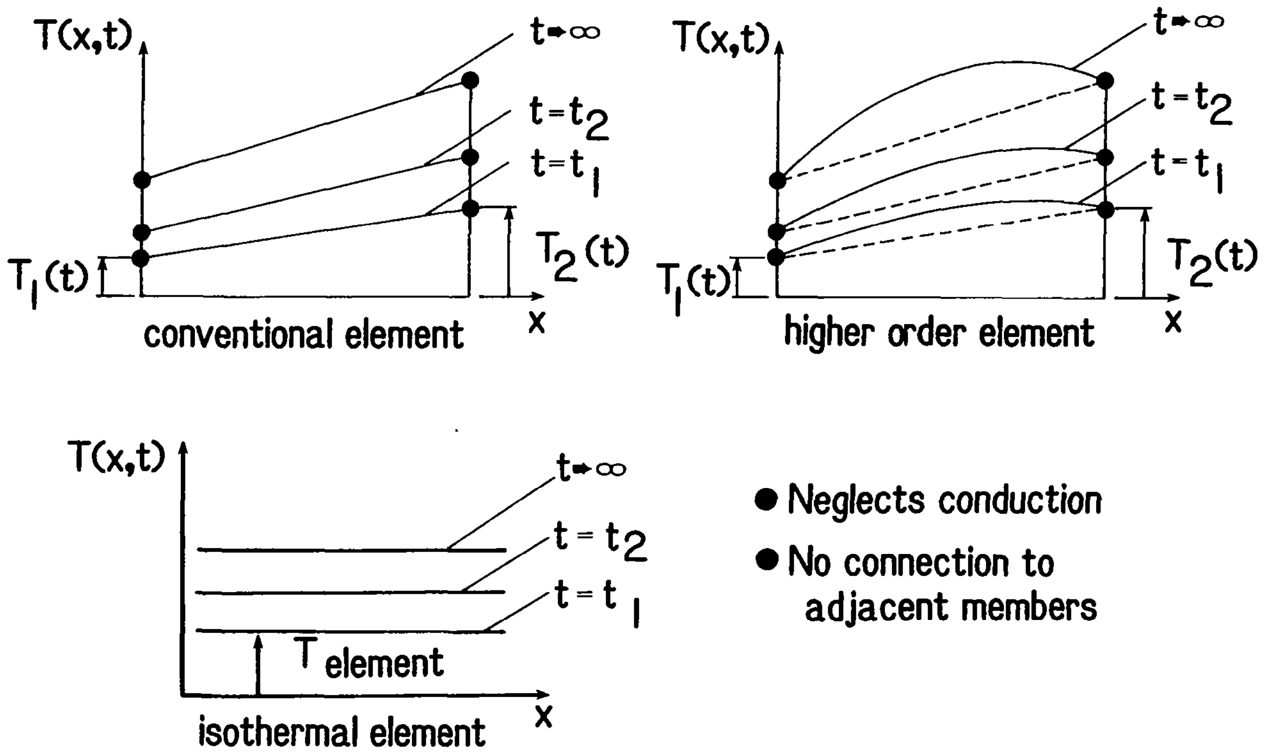


FIGURE 8

TRUSS MEMBER TEMPERATURE DISTRIBUTION

To determine the element to best model a typical space structure truss member, a repeating module of a space truss was analyzed at the noon orbit position. Member properties were representative of a tube fabricated from graphite-epoxy. Radiation equilibrium temperature distributions were computed for all members of the repeating module, but because of geometric and heat load symmetry typical results are represented by the three highlighted members (fig. 9). By symmetry, all joint temperatures are equal.

The repeating module was analyzed with: (1) one conventional element per member, (2) ten conventional elements per member, (3) one higher order element per member, and (4) one isothermal element per member.

Using the ten conventional element solution as the "exact" solution shows that a single conventional element predicts correct nodal temperatures but incorrectly predicts the temperature distribution within an element. The isothermal element, however, does an excellent job of predicting the nearly uniform member temperatures but does not predict nodal temperatures. The higher-order element (results not shown) did better than the single conventional element but tended to overestimate member interior temperatures.

For computation of the structural response, the results from the isothermal elements are superior for this low conductivity material since the average member temperature is predicted quite well. Use of these elements gives improved structural accuracy and also allows smaller, uncoupled thermal models with significant computational advantages.

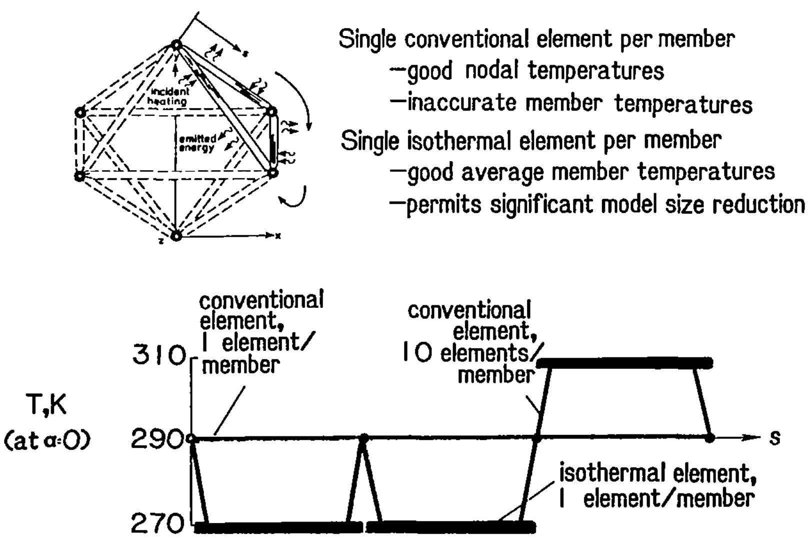


FIGURE 9

STRUCTURAL MODEL

The structural element employed is the standard two-node linear rod with a linear displacement distribution. Structural mass is neglected, so that at each point of interest in an orbit a linear quasi-static displacement analysis is performed. The average member temperatures computed by isothermal elements are used to compute equivalent thermal forces.

Note that for the heat load, thermal, and structural analyses one common geometric model has been employed (fig. 10). In each of these analyses, the analytical models have employed the geometry of the common discretization but each analysis has been "tailored" to best suit the problem. These features are fundamental characteristics of an integrated analysis.

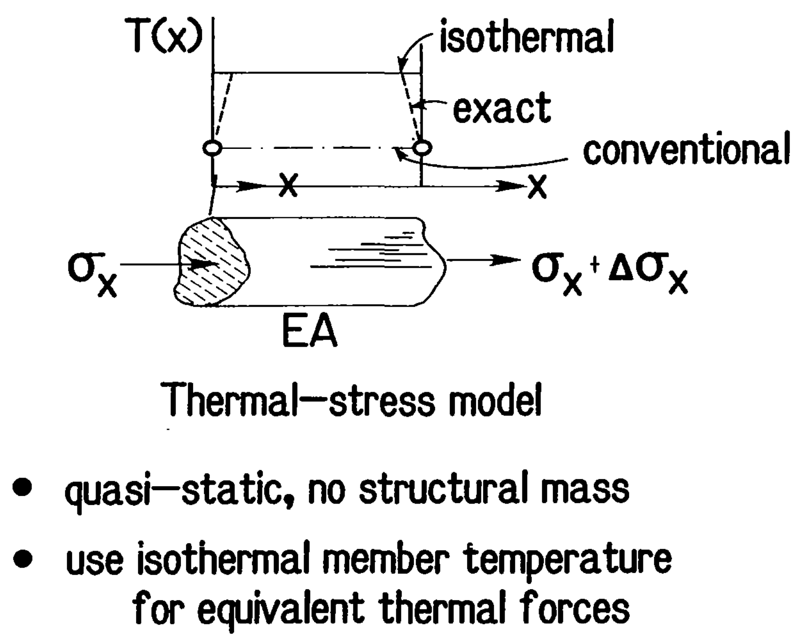
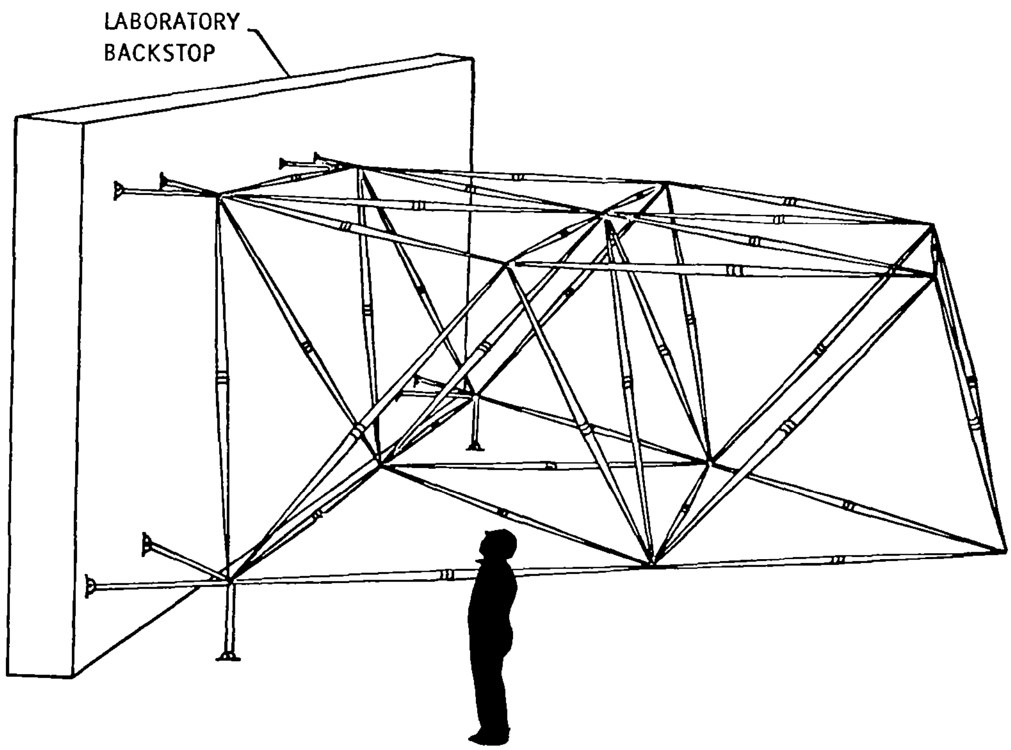


FIGURE 10

To illustrate the integrated thermal-structural analysis approach, the octetruss designed and fabricated at LaRC is analyzed. The LaRC octetruss is a 36-member space truss designed and constructed for buckling tests (ref. 7). Each member consists of two truncated cones made of graphite-epoxy members connected with aluminum joints. Each member is 5.42 meters (213.4 inches) long from end to end.

The following assumptions were made in modeling and analyzing the octetruss: (1) each member was considered to be a uniform graphite-epoxy tube, (2) the aluminum joints were disregarded, (3) each member was considered to be isothermal (conduction between members was disregarded), and (4) material properties were considered constant (fig. 11).



TYPICAL TRUSS MEMBER

- COMPOSITE MEMBER
- ALUMINUM JOINTS

FINITE ELEMENT MODEL

- ISOTHERMAL MEMBER
- ALUMINUM JOINTS NEGLECTED

FIGURE 11

TRUSS IN ORBIT

The Earth-facing octetruss is in a geosynchronous orbit in the ecliptic plane. In this orbit, the structure is in the Earth shadow for a longer time than for low Earth orbit, so that effects of the shadow on the thermal-structural response are most noticeable.

The heat load, thermal, and structural responses of the truss are computed in time increments starting from the satellite noon position ($\alpha = 0$ in fig. 12). The member temperature initial conditions are first computed from a steady-state radiation equilibrium analysis. These temperatures are used as reference temperatures for the structural analysis.

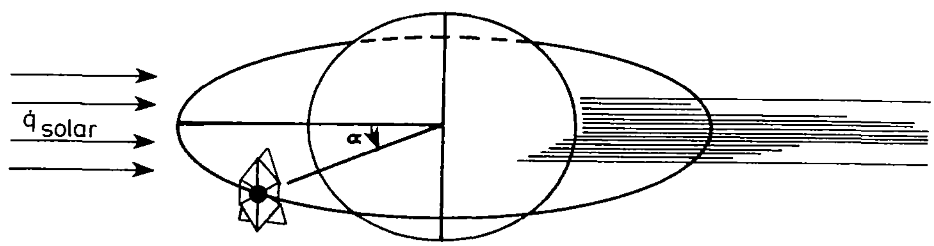


FIGURE 12

TYPICAL ELEMENT HEAT LOADS

Heating histories through one geosynchronous orbit are shown in figure 13 for three representative members of the octetruss. Note that the variation of heating rates is due solely to different member orientation with respect to incident solar heating. Because of geometric symmetry, there are six sets of members with each member of a set having the same heating history. The geometric symmetry and multiplicity of the same member heating histories occur because the octetruss is flat. In a curved space truss, such as a parabolic antenna structure, all member heating rates would differ.

The abrupt drop and rapid rise in heating occur during passage through the Earth shadow. The very low heating during shadow passage is due to Earth-emitted radiation.

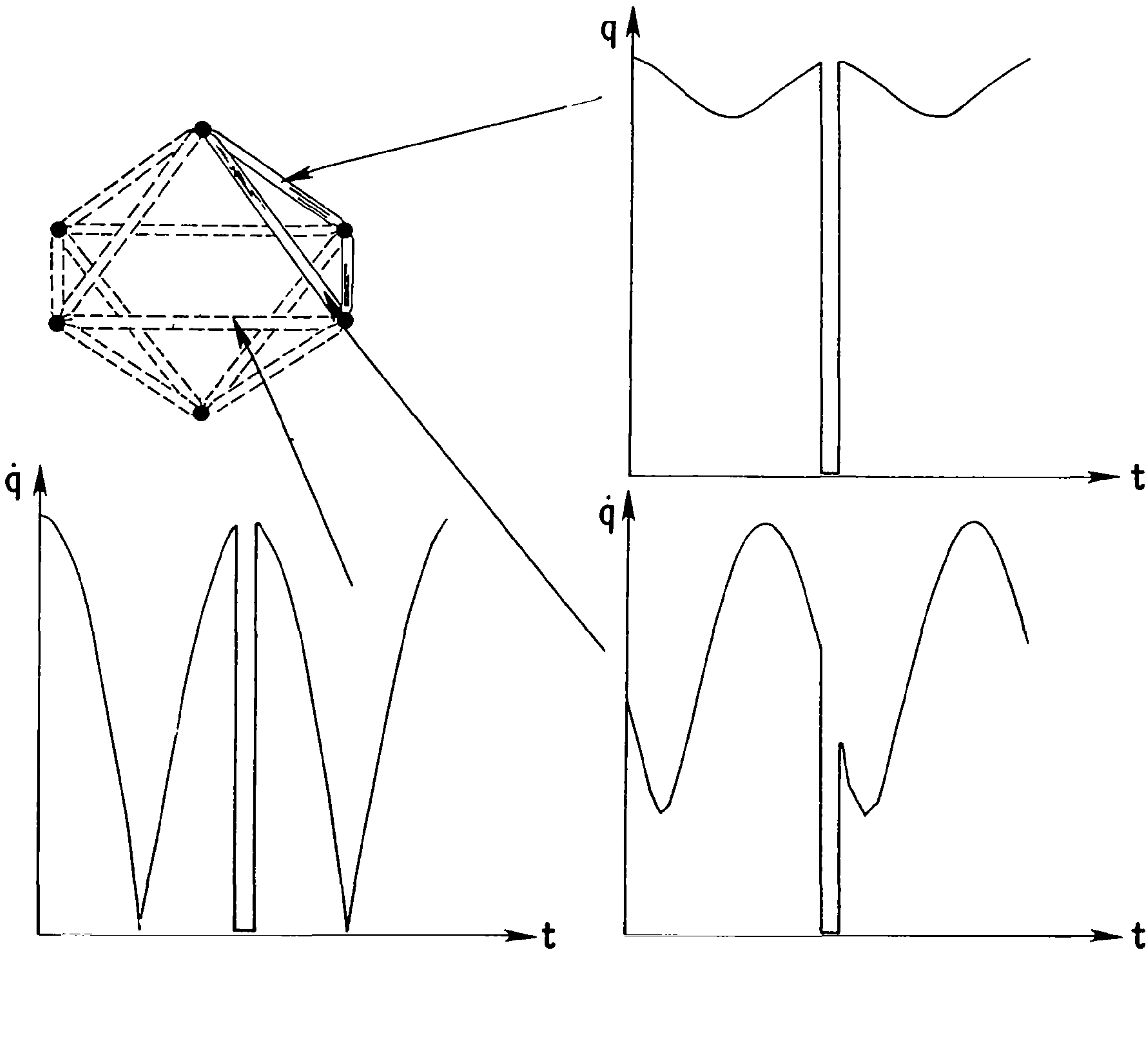


FIGURE 13

Typical member temperature histories computed from the isothermal elements are shown in figure 14. The same member families are used in temperature histories as were used in the preceding heating histories. The member temperatures follow the heating rates very closely because the members have low thermal capacitance and so stay close to radiation equilibrium. The only exception to this is the period of shadow transit, where the heating falls to almost zero abruptly and the temperatures fall more slowly toward radiation equilibrium. Upon reentering the sunlight, each member experiences a high heating with a temperature rise in the neighborhood of 6 K per second.

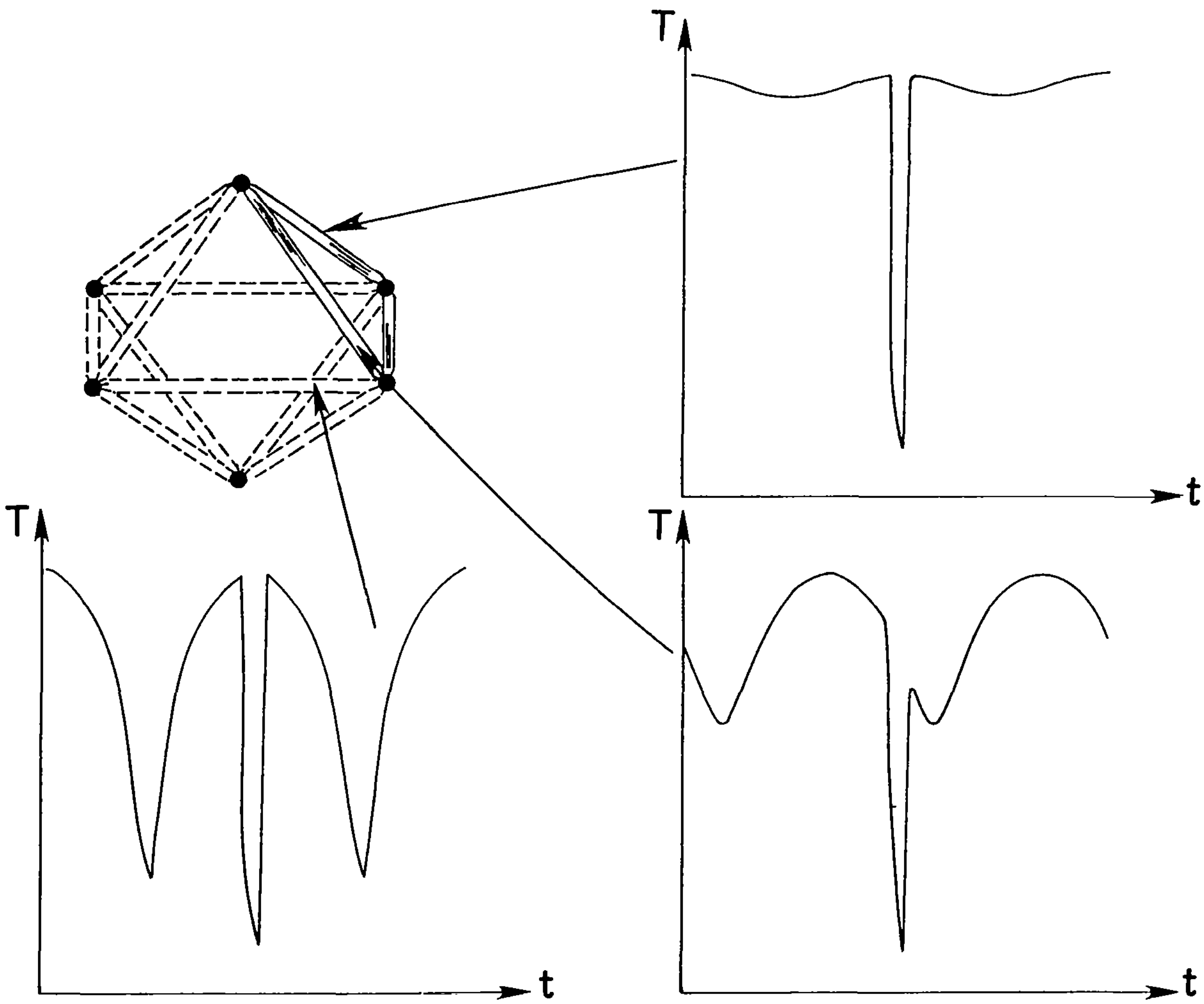


FIGURE 14

STRUCTURAL RESPONSE

Shown in figure 15 are outlines of the structure's shape at various points in the orbit. The structural response can be characterized by two features: (1) there is no out-of-plane bending due to the symmetry of the structure, and (2) the only distortion is a shearing of the top surface with respect to the bottom surface.

Notice that once the structure enters the Earth's shadow, the structure returns to its original shape. As it goes further into the shadow, however, it shrinks, getting smaller and smaller. Once the structure has reentered the sunlight, the shear deformation returns almost instantly.

Deformations shown here are greatly exaggerated; the actual deformations are just a few millimeters (the diameter of the truss is 10.8 m) due to the low thermal coefficient of expansion of the composite material. Recall, also, that the effects of aluminum joints have been neglected. Preliminary computations (not presented herein) suggest that aluminum joints with their relatively high coefficient of thermal expansion should be considered.

Member stresses exist because the truss is statically indeterminate, but they are quite small and can be neglected.

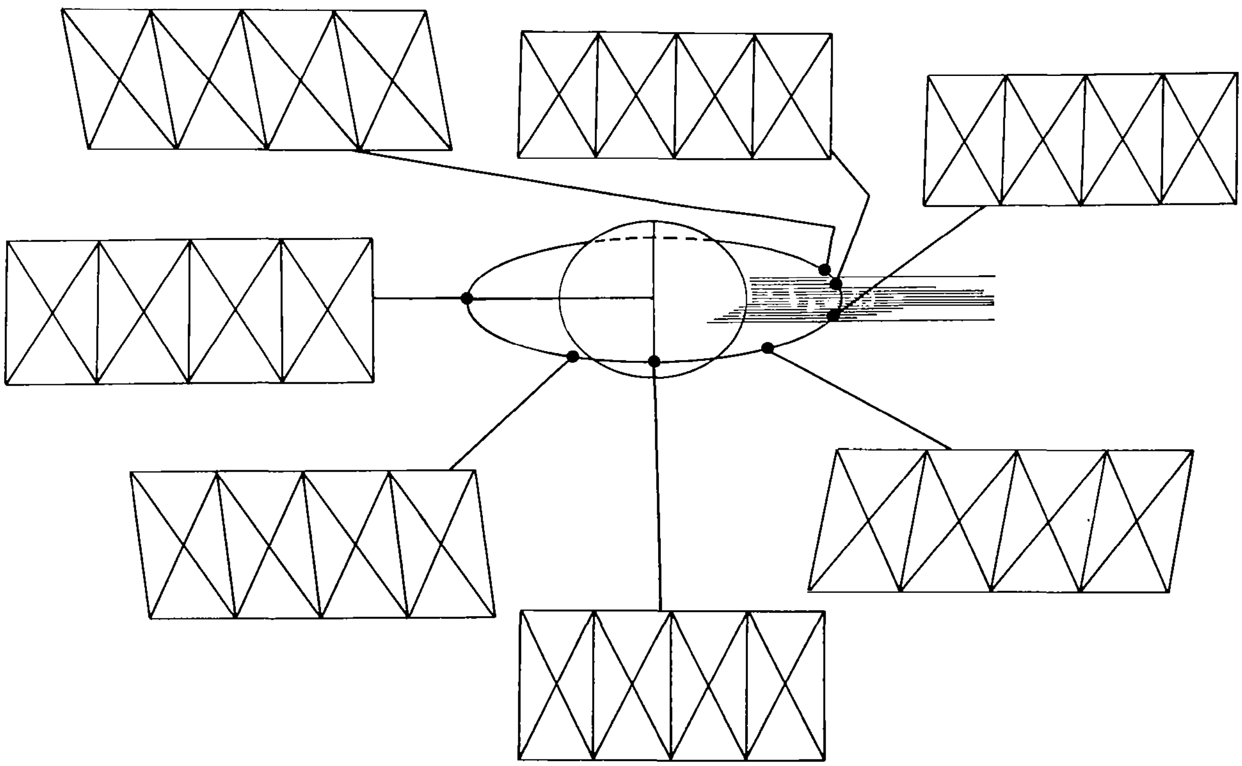


FIGURE 15

STRUCTURAL DEFORMATIONS

Two views of the octetruss structure are shown in figures 16 to 22 at the same points in the orbit that were highlighted in figure 15.

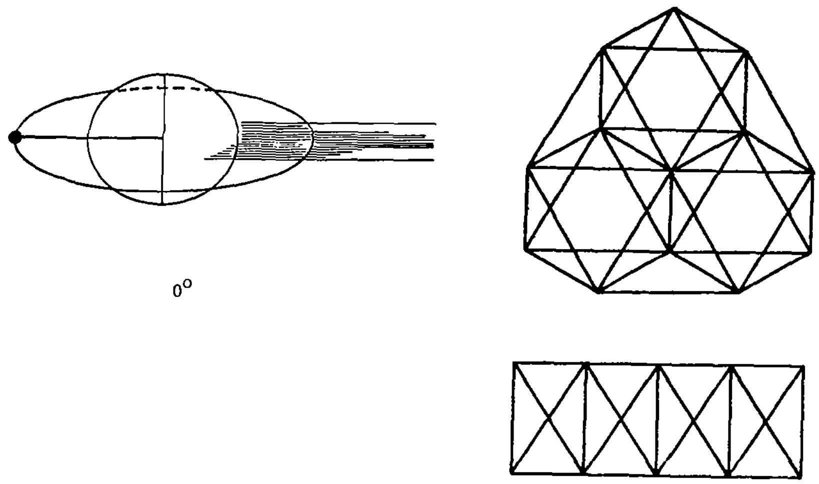


FIGURE 16

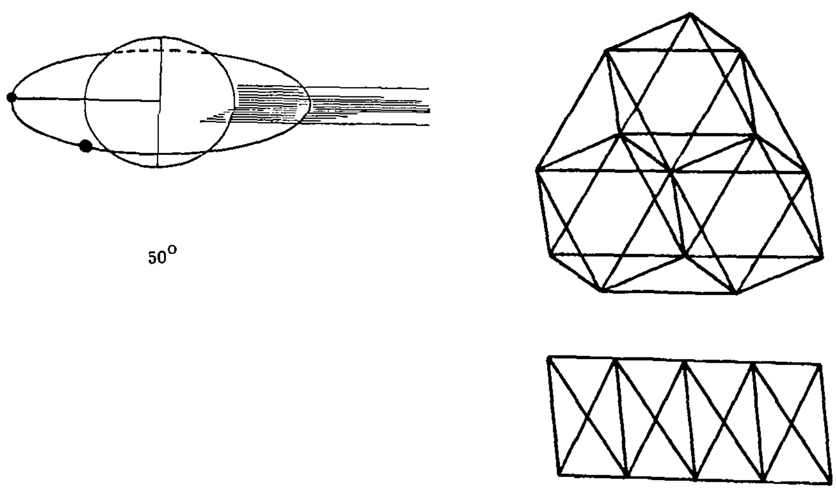


FIGURE 17

STRUCTURAL DEFORMATION

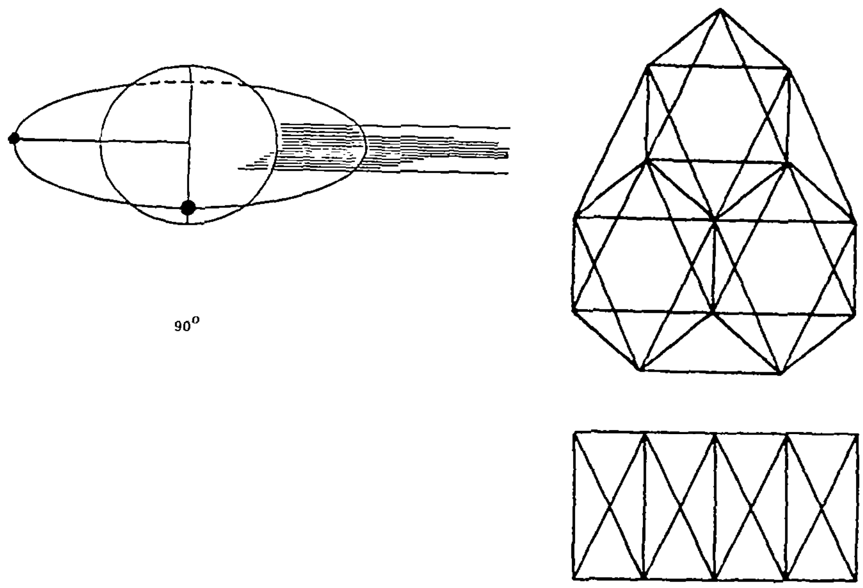


FIGURE 18

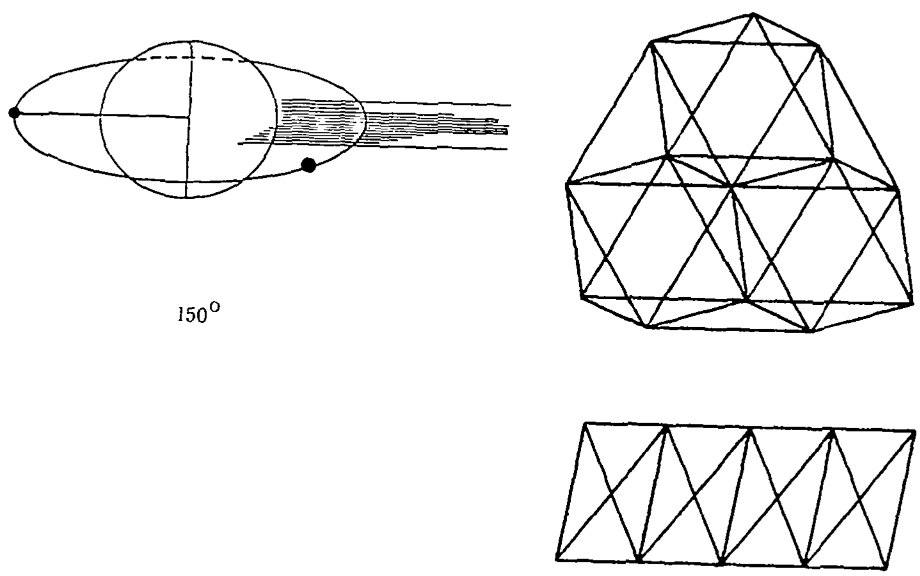


FIGURE 19

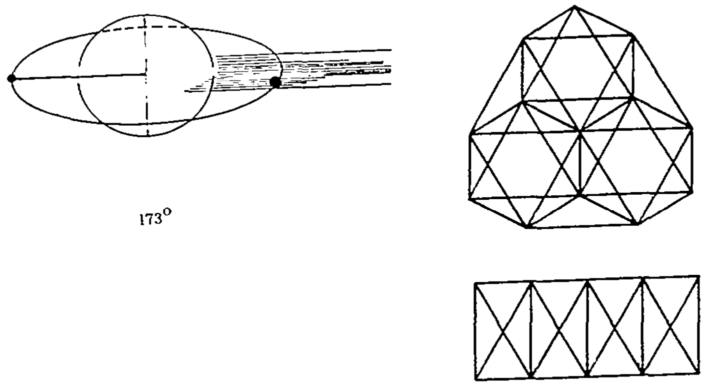


FIGURE 20

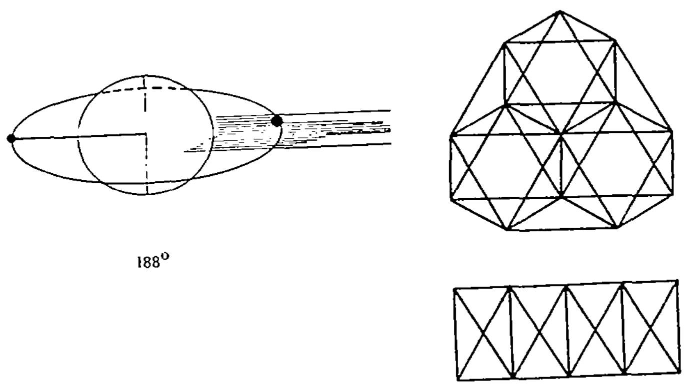


FIGURE 21

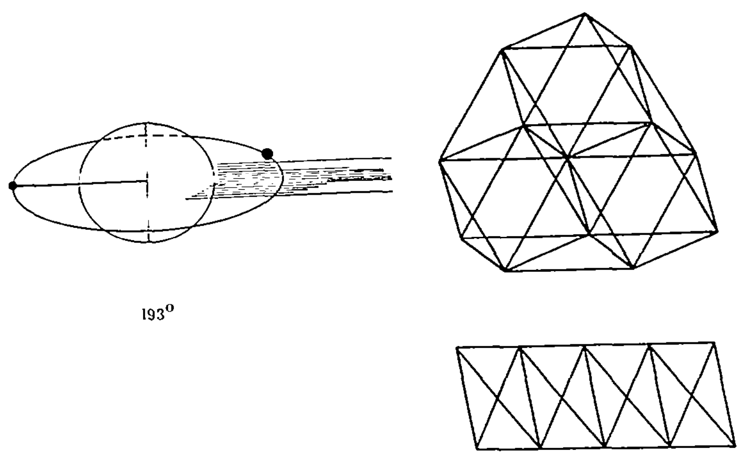


FIGURE 22

CONCLUDING REMARKS

This paper demonstrates the characteristics of an integrated thermal-structural analysis approach which employs a geometric model with a common discretization for all analyses. It allows the use of improved thermal elements and uses the results from the thermal analysis directly in the structural analysis without any intervening processing of the data.

Comparative calculations for three thermal elements show that an isothermal element works best for low thermal conductivity materials. The isothermal element gives a good representation of the member temperatures and yields the best member forces.

An illustrative example with the LaRC octetruss gives typical thermal effects on an orbiting truss structure and shows that the integrated finite element approach is an attractive method for the thermal-structural analysis of large space structrues (see figure 23).

- CHARACTERISTICS OF INTEGRATED APPROACH
  - GEOMETRIC MODEL WITH COMMON DISCRETIZATION
  - IMPROVED THERMAL ELEMENTS
  - STRUCTURALLY INTEGRATED THERMAL RESULTS
- THREE TRUSS THERMAL ELEMENTS DESCRIBED FOR CONDUCTION COMBINED WITH RADIATION
- ISOTHERMAL ELEMENT BEST FOR LOW CONDUCTIVITY MATERIAL
  - GOOD REPRESENTATION OF MEMBER TEMPERATURES
  - BEST MEMBER FORCE
- OCTETRUSS EXAMPLE ILLUSTRATED TYPICAL ORBITING STRUCTURE RESULTS
- INTEGRATED FINITE ELEMENT APPROACH ATTRACTIVE FOR ORBITING STRUCTURES ANALYSIS

FIGURE 23

ACKNOWLEDGEMENT

This paper was based upon research supported by NASA Langley Research Center under grant NSG 1321.

REFERENCES

1. Thornton, Earl A.; Dechaumphai, Pramote; and Wieting, Allan R.: Integrated Thermal-Structural Finite Element Analysis. Proceedings of the AIAA/ASME/ASCE/AHS 21st Structures, Structural Dynamics, and Materials Conference, May 12-14, 1980, Seattle, Washington, AIAA Paper No. 80-0717, pp. 957-969.

2. Thornton, Earl A.; Dechaumphai, Pramote; Wieting, Allan R.; and Tamma, Kumar K.: Integrated Transient Thermal-Structural Finite Element Analysis. Proceedings of the AIAA/ASME/ASCE/AHS 22nd Structures, Structural Dynamics, and Materials Conference, April 6-8, 1981, Atlanta, Georgia, AIAA Paper No. 81-0480, pp. 16-32.

3. Cunningham, F. G.: *Power Input to a Small Flat Plate from a Diffusely Radiating* Sphere with Applications to Earth Satellites. NASA TN D-710, 1961.

4. Modest, M. F.: Solar Flux Incident on an Orbiting Surface after Reflection from a Planet. AIAA Journal, June 1980, pp. 727-730.

5. Kreith, Frank: Radiation Heat Transfer for Spacecraft and Solar Power Plant Design. International Textbook Co., pp. 95-96, 1962.

6. Chambers, B. C.; Jensen, C. L.; and Coyner, J. V.: An Accurate and Efficient Method for Thermal-Thermoelastic Performance Analysis of Large Space Structures. AIAA 16th Thermophysics Conference, June 23-25, 1980, Palo Alto, California, AIAA Paper No. 81-1178.

7. Card, M. F.; Bush, H. G.; Heard, W. L. Jr.; and Mikulas, M. M. Jr.: Efficient Concepts for Large Erectable Space Structures. Large Space Systems Technology, NASA CP-2035, 1978, pp. 627-656.