Thermal-Structural Analysis of Large Space Structures: An Assessment of Recent Advances

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Introduction

CONCEPTS of orbiting space structures that are under development present structural analysts with significant challenges in analysis and design. The large size of the structures makes them distinct from past Earth satellites. Deployable antenna concepts up to 100 m and erectable structures of several hundred meters in diameter are under consideration. To gain low weight and high stiffness, the structures typically employ open, latticework construction. Designs include pretensioned, cable-stiffened structures, and space trusses. To achieve low weight and high stiffness, and to minimize thermal distortions, the designs make extensive use of advanced composite materials.

Often an important design constraint lies in controlling structural deformation within close tolerances. Operational requirements for a 100-m antenna design can limit surface distortions to a few millimeters. Such stringent operational requirements have focused attention on analysts' capabilities for predicting small deformations with high accuracy. An important factor emphasizing the need for effective analysis methods is that the size of the proposed structure will prohibit the ground testing customary for past spacecraft.

Large space structures activities from 1973 to 1979 are reviewed in Ref. 1. The proceedings[2-6] of a series of annual conferences focused on Large Space Systems Technology (LSST) provide a good review of LSST research and development. A bibliography[7] provides a selection of annotated references to unclassified reports and journal articles. This paper is based primarily on references from these sources and from information gathered during visits to six aerospace companies in January 1983. A significant amount of information on recent work on space structures is probably unavailable to the general scientific community because it is unpublished, proprietary, or classified.

The control of large space structures' deformations within small tolerances requires careful consideration of several effects on the structural response. Thermally induced forces are only one of several on-orbit loads that must be considered, including pretensioning, orbital positioning thrusts, gravity gradient forces, and atmospheric drag. The determination of thermal forces is a complex, interdisciplinary problem requiring consideration of orbital mechanics, heat transfer, and structural mechanics. Several studies that appear in Refs. 1-7 have considered isothermal structural analyses (e.g., buckling and vibration behavior), but not many studies have included thermal effects. A few studies using simplified techniques[8,9] have estimated the behavior of orbiting trusses. There has been little fundamental published research on thermal-structural response of large space structures, however. Researchers have not fully recognized that thermal analysis of many large latticework structures may be impractical using available computer programs because of the great number of unknowns required to analyze such structures. In addition to the large comptutational cost of analyzing large space structures, there are significant uncertainties in the three key analyses required to predict large space structures' thermal deformations accurately: 1) heat load analysis, 2) thermal modeling and temperature analysis, and 3) structural modeling and deformation analysis.

The purposes of this paper are to review recent advances in modeling, analysis, and understanding of thermal-structural responses of large space structures, and to identify uncertainties in the thermal-structural analysis. Typical heat load, thermal, and structural analysis requirements for large space structures will be discussed by using a design of a future large spacecraft to illustrate specific modeling and analysis characteristics. Then the current status of heating, thermal and structural analyses will be reviewed. Finally, the computer programs used in research and design will be identified and discussed. Trends in computer program development will be highlighted.

Microwave Radiometer Spacecraft

The design details of a microwave radiometer illustrate a few of the complexities of thermal-structural analysis. The

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microwave radiometer spacecraft (MRS) concept was employed in a study to develop a computer program for the design of Large Advanced Space Systems (LASS). The details of LASS and the microwave radiometer concept are taken from Leondis[10] and Garrett.[11]

Microwave Radiometry

Passive microwave radiometry can be used in remote sensing of soil moisture to support crop forecasting. Microwave frequencies that penetrate clouds, haze, and ground cover are monitored. A large-aperature, smooth-surface antenna is required to capture and focus the low-signal Earth radiation on sensors. The resulting measurements are brightness temperatures that are functions of soil ambient temperatures and emissivity, where the emissivity is strongly dependent on soil moisture content. The proposed MRS system would be placed at orbital altitude of 650 km or more with a +60 deg, sun-synchronous orbit inclination. The antenna would have a 725-m diameter, a focal length of 575 m, a surface accuracy of approximately 6 mm, and a pointing accuracy of 0.01 deg.

Spacecraft Details

The MRS structure and supporting systems are shown in Fig. 1. The structure is a graphite composite, tetrahedral truss made from hollow tubes with an RF reflective mesh (aluminized Kapton) attached to offsets on the concave surface. Graphite composite support beams and Kevlar tension cables provide control for feed horns mounted on a graphite composite feed beam located at the focal point of the reflector. The antenna dish is a spherical segment with the feed beam oriented normal to the spacecraft velocity vector. The MRS tetrahedral truss concept is a relatively small, four-ring truss with 109 joints and 420 members. Other concepts discussed in Refs. 10 and 11 include more complex designs such as a 12-ring truss with 901 joints and 3,852 members.

Altitude control is provided by an annular momentum control device and eight liquid oxygen/liquid hydrogen thrusters. The spacecraft is assumed to undergo one maneuver every five orbits with maneuver rates and accelerations of 10^{-4} rad/s and 10^{-6} rad/s^2, respectively. Orbital velocity makeup is provided by four thrusters. Three propellant tanks carry a three-year fuel supply. The MRS is designed for a 15-year lifetime.

The MRS system is representative of many large space structures characterized by large latticework structures, pretensioned cables, tubular tension and compression members, and extensive use of advanced composite materials. Several other antenna designs have been developed (Refs. 2-6). Preliminary design and system studies have been completed establishing the designs' capabilities to meet mission requirements. Detailed design and verification studies of the various designs are in different stages of progress throughout the industry.

Heating Analysis

Heat Loads

An orbiting space structure may be heated by environmental and on-board heat sources. The sun and Earth are the primary environmental sources. Onboard heating can come from many sources such as prime power systems, electronics equipment, and heat rejection systems.

Table 1 Orbital data

			Transient time, s	
Orbit	Period, s	Altitude, km	Umbra	Penumbra
GEO	86,400	35,800	41,700	130
LEO	5,400	280	2,200	8

Environmental heating rates, the sum of solar flux, Earth-emitted radiation, and Earth-reflected radiation (albedo), depend strongly on altitude and orientation of structural members. Heating rates on members of a structure may vary significantly with member orientation and vary strongly with time during the orbit. Heating rates can be reduced by as much as 95% during spacecraft passage through the Earth's shadow; hence, shadow dwell time is important. Fundamental concepts of spacecraft orbital heating are described in Ref. 12, and a computational procedure for predicting environmental heating on structural members is described in Ref. 13. Representative orbital data is tabulated in Table 1 for a geosynchronous Earth orbit (GEO) and for a low-Earth orbit (LEO).

The Earth's shadow has two regions, 1) the umbra, which is totally shadowed from the sun, and 2) the penumbra, which is only partially shaded. Table 1 gives the transit times of a structure through the umbra and penumbra in GEO and LEO. Since the transient time through the penumbra is negligible compared to that through the umbra, the penumbra can be disregarded and the structure can be considered to have entered the umbra directly.

In flat truss structures there may be several members with a common orientation so that these members experience the same heating throughout the orbit. A heating analysis of a curved structure, such as the spherical MRS tetrahedral truss

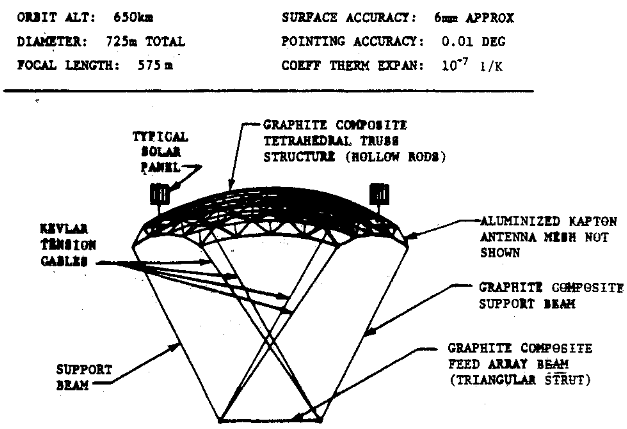

Fig. 1 Microwave radiometer spacecraft.[11]

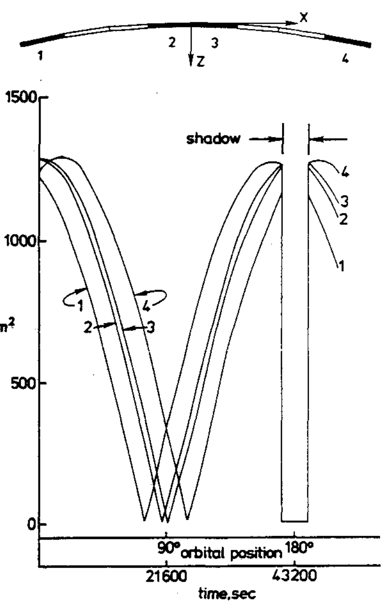

Fig 2 Heating histories for parabolic truss in GEO.[13]

(Fig. 1), must consider all members individually because there are no similarities in orientation. Mahaney and Strode[13] discuss environmental heating on an Earth-facing parabolic tetrahedral truss in an ecliptic plane orbit. Two results (Figs. 2 and 3) may be used to illustrate details of structural heating rates. Figure 2 presents heating histories of four members on the main diagonal of a parabolic truss in GEO. Figure 3 presents the heating histories of the same four members in LEO. There are two major differences: 1) the magnitude of the heating is greater because this orbit is closer to the Earth, and 2) shadow transit covers about 41% of the orbit in LEO vs only about 4.8% in GEO.

On-board heating may be more important than environmental heating in future large space structure thermal-structural effects. A conference in February 1982[14] indicated the need for the development of prime power systems of 10- to 100-kW output. Thermal management of waste heat could have a more significant effect than environmental heating because of higher levels of on-board heating, and because heating distributions from on-board heat sources will be more localized. There has been very little published research on the effect of on-board heating. One study of a two-tier flat truss structure in LEO[15] showed that without on-board heating there was no appreciable curvature of the truss, but nonuniform, on-board heating of the truss induced small truss curvatures.

Shadowing Effects

For large space structures such as the MRS system (Fig. 1) there are three types of shadowing effects: 1) shadowing of the structure by opaque surfaces such as the solar panels; 2) partial shadowing by large semitransparent surfaces such as the antenna mesh; and 3) shadowing of structural members by slender structural members. Detailed consideration of any of these shadowing effects is difficult because of the complex geometry involved and the time-dependent character of the problem. Few results have been published on the effects of shadowing the structure with opaque surfaces such as solar panels. The consideration of such effects is closely related to the conduction-radiation heat transfer problem and can be handled (presumably) by available computer programs. (Computer programs used in heat load, thermal and structural analyses are discussed briefly in a later section.) Partial shadowing of large space structures by antenna meshes is discussed in Refs. 10 and 16. These analysts use a mesh transmissivity that depends on mesh characteristics (e.g., openings per inch) and the angle of incidence between the heating vector and the mesh normal. Chambers, Jensen, and Coyner[16] show that the mesh can cause complete shadowing of the structure at points during an orbit, and that a detailed consideration of mesh shadowing is critical for defining structural heating.

Consideration of shadowing by slender structural members has been customarily omitted for a latticework structures such as trusses. This assumption has been questioned[17] particularly for nearly planar, Earth-facing structures. For these structures, significant shadowing can occur when the solar vector is nearly tangent to the orbital path. O'Neill and Zich[17] describe a computer program developed to quantify the complex solar shadowing inherent in lattice-type structures. The computer program computes incident heat fluxes at specified points on each member considering partial shadowing of adjacent members. The effects of slender-member shadowing at a typical point on a truss member are illustrated by the temperature history shown in Fig. 4. The numerous short-duration drops in temperature indicate the passage of shadows of adjacent truss members. The large, longer-duration temperature drop near the center of the history denotes passage through the Earth's shadow. The process of predicting the details of slender-member shadowing effects is quite complex and therefore is expensive for a truss with hundreds of members. Thus an important question arises: Is the consideration of slender-member shadowing effects required for accurate prediction of structural deformations?

Thermal Analysis

A typical member of a space structure experiences conduction heat transfer combined with radiation heat exchanges from nearby structural members and the other spacecraft components. The discussion herein is limited to the unique thermal analysis problems of large latticework structures such as the MRS shown in Fig. 1.

Thermal Modeling

In an open latticework structure, radiation exchanges between members can be neglected in comparison to incident heating and emitted radiation. Chambers et al.[16] show that the view factor between two nearby members in an open structure is typically less than 0.001, indicating that almost all of the radiant energy emitted by a member is lost to space. In general, structural members' temperatures vary along their lengths and around their perimeters. Most truss members are hollow rods (tubes) and internal radiation may be significant. Thermal analysis of a large truss taking all of these details into account is impractical because of the prohibitively large number of unknowns required. Consequently, a number or simplifying assumptions are customarily made to permit thermal analysis at acceptable costs. Simplified thermal models are discussed in Refs. 8, 16, and 18-21. In the following discussion, models for bare members or members

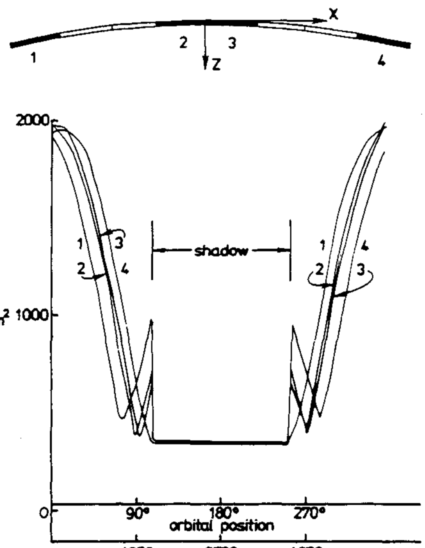

Fig. 3 Heating histories for parabolic truss in LEO.[13]

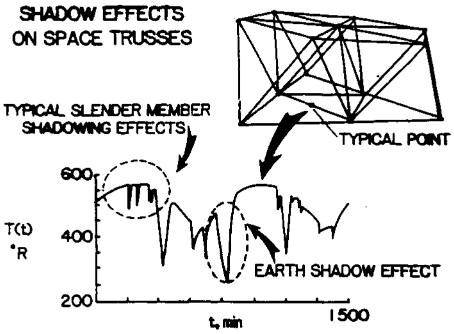

Fig. 4 Slender member shadowing effects at a typical point in a space truss.[17]

with surface coatings are considered; modeling considerations for insulated or shielded members are discussed by Brogren, Barclay, and Straayer.[8]

Structural-member temperature distributions depend strongly on material and surface properties. In general, material and surface properties are temperature-dependent and vary throughout the orbit. Thermal properties of composite materials such as graphite-epoxy are difficult to measure and not readily available. In addition, little information is available about the stability of these properties in long-duration exposure to the hostile environment of space.

The thermal conductivity of metallic materials (aluminum or metal matrix composites) is much higher than the thermal conductivity of a resin matrix (graphite-epoxy) composite material. Temperature distributions in members made from these materials differ significantly, and these differences have an important effect upon the required analytical models. For instance, Brogren, Barclay, and Straayer[8] show that the temperature variation around the perimeter of an aluminum tube (ratio of outside diameter to wall thickness = 25) subject to solar heating in LEO is negligible. However, they show that the temperature variation around the perimeter of a graphite-epoxy tube (ratio of outside diameter to wall thickness = 100) is significant. At a typical point in LEO, the temperature of the side of a tube exposed to solar heating was 352 K, while the shaded side of the tube registered 262 K.

In addition to the temperature variation around the tube perimeter, member temperatures may vary along their length due to axial conduction. For trusses, a member's mean temperature can be denoted as $T(x,t)$ where x is an axial coordinate and t is time. The mean temperature satisfies the energy balance equation

$$-\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)+\sigma\epsilon T^4 p+\rho c A\frac{\partial T}{\partial t}=a p_q q(t) \qquad (1)$$

where k is the thermal conductivity, A is the cross-sectional area, σ is the Stefan-Boltzmann constant, ϵ is the emissivity, p is the member radiation perimeter, ρ is the density, c is the specific heat, a is the surface absorptivity, p_q is the projected perimeter for incident heating, and $q(t)$ is the incident heating rate. Equation (1) shows that a member's axial temperature variation depends on the combination of conduction and radiation heat transfer. In Ref. 19-21, there are studies of typical truss-member temperature distributions using the finite-element method. Temperature distributions of aluminum and graphite-epoxy composite members differ significantly. Aluminum members have a more nonuniform temperature distribution than composite material members. Temperature distributions along composite members are so nearly uniform that if joints are neglected it is valid to assume that a single truss member is isothermal. With the finite element approach (Refs. 20 and 21), one isothermal finite element per member can be used, or with the finite difference network-type approach (Refs. 10 and 16), each member can be represented as a single node. In both cases, the conduction term can be neglected in Eq. (1) to yield an ordinary differential equation for each member

$$\sigma\epsilon T^4 p+\rho c A\frac{dT}{dt}=a p_q q(t) \qquad (2)$$

where the temperature is a function only of time, $T(t)$. Thus, for trusses with composite members, each member's mean temperature can be computed separately by solving Eq. (2). Temperatures in a truss with composite members can be computed easier than in a truss with aluminum members where each member's spatial temperature distribution must be computed. Equation (2) can be solved in closed-form[17] to yield a transcendental equation which is solved by Newton-Raphson iteration or can be solved by a combination of finite differencing in time and Newton-Raphson iteration.[19-21]

The isothermal concept is widely used for preliminary design analysis of large space structures such as the MRS system. Chambers, Jensen, and Coyner[16] modify the radiation term in Eq. (2) with a correction factor to account for heat conduction around the tube perimeter; graphs of correction factors for cylindrical and square tubes are given vs a characteristic tube parameter. Chambers et al. also describe an approximate method of computing the diametrical temperature difference due to perimeter heat conduction and interior radiation heat transfer. Calculation of these temperature gradients is important in determining bending

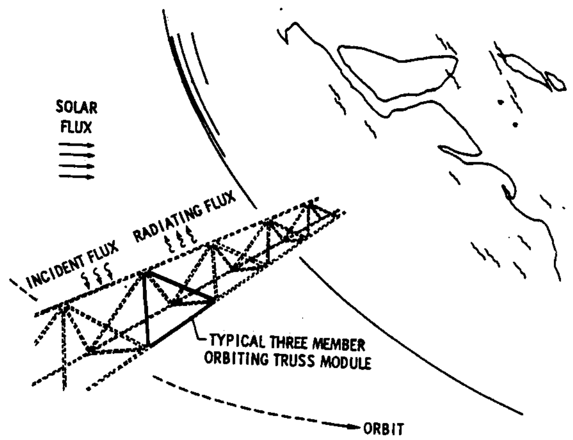

Fig. 5 Orbiting truss space structure.[21]

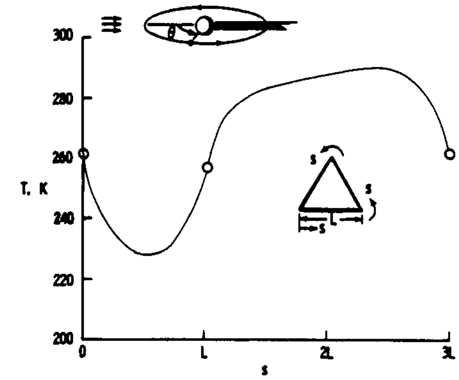

Fig. 6 Temperature distribution of a three-member orbiting aluminum truss at $\theta = 60$ deg.[21]

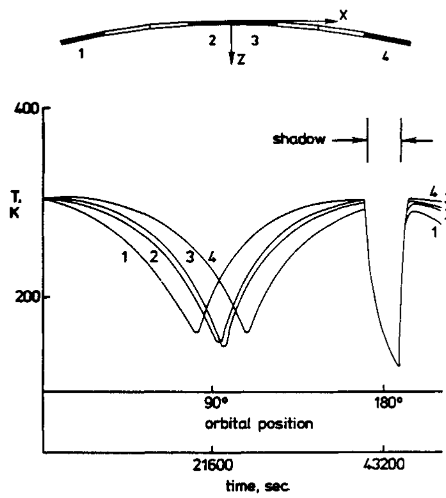

Fig. 7 Temperature histories for parabolic truss in GEO.[12]

deflections that result in a reduction of the structural-member allowable column buckling load. Temperature distributions in the cross-section of laminated composite tubes may also be important for the long-term fatigue behavior of the composite, but little research has been performed to evaluate this effect.

Thermal Response

As the preceding paragraph indicates, the space structure material determines the required thermal model and may determine the method of computing the thermal response. Certainly for all-composite material structures, the isothermal-member model is an excellent approximation and leads to an uncoupled thermal-analysis approach where Eq. (2) is solved separately for each member. For a metallic structure or a non-homogeneous structure with both metallic and composite members (e.g., joints), a more general analysis is required to determine member spatial-temperature distributions as a function of time. In general, a set of coupled, nonlinear equations of the form

$$[C(T)]\left\{\frac{\mathrm{d}T}{\mathrm{d}t}\right\}+[K(T)]\{T\}=\{Q(t)\} \tag{3}$$

is solved for the temperatures $\{T(t)\}$ at discrete nodal points in the structure. The matrix $[C(T)]$ represents the structure's capacitance, and $[K(T)]$ represents the structural conduction and radiation heat transfer; both matrices depend on the nodal temperatures. The vector $\{Q(t)\}$ represents time-dependent nodal heat loads. The coefficient matrices may be formed from either a finite-difference network-type model or a finite element model. Nonlinear, time-dependent equations such as Eq. (3) are typically solved by finite differencing in time.

To illustrate characteristics of large space structures' thermal response, Figs. 5-8 present results of analyses of aluminum and graphite-epoxy trusses. A three-member module of an orbiting truss (Fig. 5) is useful for illustrating temperature distributions in aluminum members. The temperature distribution on the members at a typical point in a GEO is shown in Fig. 6.

Transient temperature histories for four members of a graphite-epoxy tetrahedral truss are shown in Figs. 7 and 8. The temperature histories shown in these figures were computed using the isothermal member concept, and they correspond to the heating histories for the same members shown in Figs. 2 and 3.

Figure 8 presents the temperature histories of the same four members in LEO. As before, the temperature histories are similar to the heating histories; however, there are two important differences. First, in LEO the truss is never at radiation equilibrium. Radiation equilibrium is not achieved because the shorter orbital period causes the heating rates to change much faster. Thus the transient term in Eq. (2) has a much greater effect in LEO than in GEO. Second, the much greater heating of the Earth increases the magnitude of the temperatures, but it also moderates temperature excursions.

Other advances in thermal modeling and analysis of spacecraft and satellite antennas, in addition to those of latticework structures appear in Refs. 22-24.

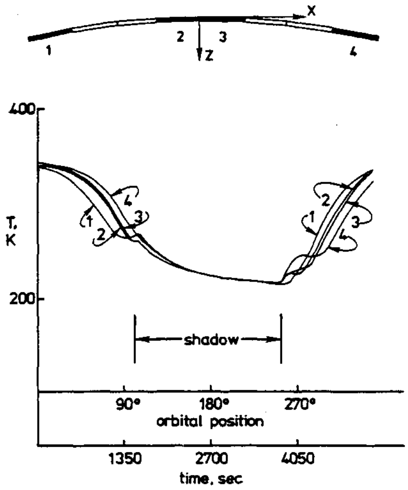

Fig. 8 Temperature histories for parabolic truss in LEO.[12]

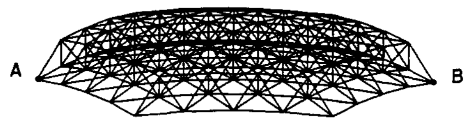

Fig. 9 Parabolic tetrahedral truss.[13]

Structural Analysis

In most analyses of the thermal-structural responses of orbiting large space structures, the thermal input is regarded as a known function of time. This approach, based on uncoupled analyses, assumes that structural deformations are small enough that absorbed heating and temperature distributions are unaltered by the structural deformations. In uncoupled thermal-structural analyses, structural deformations and stresses are determined as the final step in a sequential computation of heat loads, thermal response, and structural response. In some problems, however, structural deformations may be large enough to alter heat loads and temperature distributions, requiring a coupled thermal-structural analysis. The following discussion first considers uncoupled thermal-structural analysis.

Structural Modeling

The thermal structural response of a complex space structure like the MRS system shown in Fig. 1 is usually computed from a finite element model. The complete structure is represented as an assembly of elements chosen to represent the structural characteristics of the beams, cables, and truss members. The thermal environment affects the structural analysis through 1) material properties that may be temperature-dependent, and 2) equivalent thermal forces and moments that depend on integration of the temperature distributions over member volumes. Two types of structural models have been considered, discrete models in which finite elements are used to represent structural members in detail, and continuum models which replace a lattice-type structure with repetitive geometry by an equivalent elastic continuum such as a beam or a plate.

The discrete model approach gives the best representation of the space structure's mass, stiffness, and equivalent thermal loads. With the exception of pretensioned cables and membranes, major structural components such as trusses and beams exhibit linear behavior and can be analyzed effectively using linear, small deflection, finite element programs. However, pretensioned cables and membranes are known to have significant nonlinear force-deflection characteristics and may experience large deflections and, consequently, warrant nonlinear analysis.[25,26] Little information is available on effective modeling methods for these structural components either in the isothermal state or with thermal effects. A recent study of isothermal vibrations and buckling of a pretensioned cable-stayed column[27] showed that: 1) experimental verification of analytical models is difficult; 2) structural imperfections are important; 3) dynamic loading affects the required pretension; and 4) cable slackening may produce significant nonlinearities. There is a clear need for further study of cable and membrane behavior in large space structures, particularly in the presence of the thermal environment.

Using the discrete finite-element model approach for a large space structure can lead to analytical models with a large number of nodes. However, structural mass and stiffness matrices are highly banded, and computational costs may be acceptable. Mahaney and Strode[13] show that matrix semibandwidth is of the order of 10% of the number of nodal unknowns for tetrahedral trusses.

Continuum models[28,29] have been developed as a practical solution method for overall response and preliminary design studies. The continuum models are shear flexible beams and plates. Equivalent elastic constants are developed for the continuum models in terms of material properties and geometry of the original lattice structure. For overall isothermal structural behavior such as vibration and buckling, continuum models give excellent agreement in numerical examples for beam- and plate-like lattice grids. The accuracy of the approach for more realistic space structures has not been evaluated. In realistic large space structures with thermal loads, there are a number of effects that limit the usefulness of continuum models. For instance, in a dished lattice-type structure, temperatures vary significantly from member to member and with time as the structure continuously changes its orientation with the solar vector. Consideration of this type of temperature distribution and local temperature dependence of material properties is beyond the capability of continuum models. Nevertheless, continuum models are useful in preliminary design; the LASS program[10] uses the concept of an analogous structure based on continuum modeling to reduce the cost of structural analysis.

Material Properties

Advanced composite materials are widely used in large space structures because of their high stiffness and low coefficients of thermal expansion (CTE). Reliable material data is a prerequisite to accurate thermal-structural response predictions. The determination of this data for advanced composites in the space environment is difficult and is the subject of current research. The major environmental parameters in the space environment are low pressure (high vacuum), ultraviolet radiation, ionizing radiation, and thermal cycling. References 30-34 describe these environmental effects and present recent advances in measurement of the CTE and the effects of space environment. The CTE of a composite member depends on the laminate layup and the material properties of individual lamina. Johnson, Kural, and Mackey[35] present a compilation of CTE data for composite materials and a procedure for computation of lamina properties by lamination theory. The stability of structural material properties in a long-term space environment is not well understood. Experiments described in Ref. 32 indicate that significant changes occur in the CTE because of the combined effects of vacuum and thermal cycling. There is a clear need for continued materials reseach to further the understanding of this kind of behavior in the space environment.

Structural Response

In an uncoupled thermal-structural analysis, the structural deformations do not appreciably affect the heat loads, and the analyses may be performed sequentially without iteration. In a coupled thermal analysis, the structural deformations alter the heat loads, and the thermal-structural response must be computed iteratively. In an uncoupled thermal-structural response analysis using a discrete model, the large space structure displacement response $\{u(t)\}$ is computed from the general structural dynamics equation of motion:

$$[M]\{\ddot{u}\} + [C_d]\{\dot{u}\} + [K]\{u\} = \{F_T(t)\} \tag{4}$$

where $[M]$ is the mass matrix, $[C_d]$ is the damping matrix, $[K]$ is the stiffness matrix, and $\{F_T(t)\}$ is the equivalent

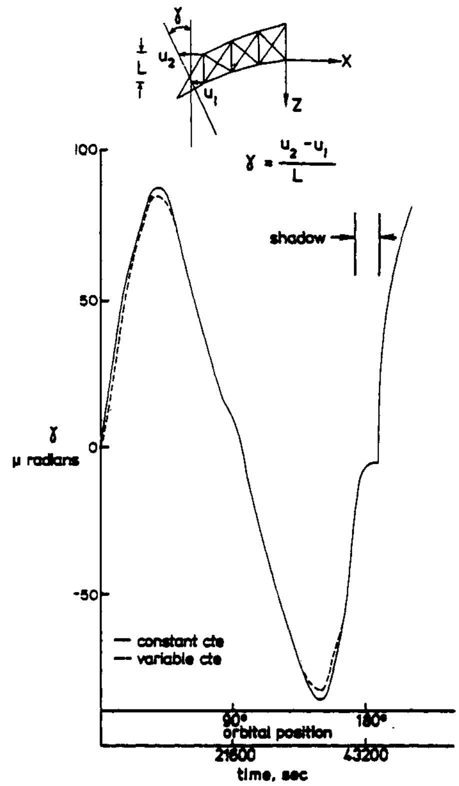

Fig. 10 Truss change in diameter history.[13]

nodal forces due to the time-dependent member temperature distributions. The mass matrix is independent of temperature, but the damping and stiffness matrices are implicit functions of temperature because of temperature dependence of material properties. Thus, in numerical solutions to Eq. (4) these matrices must be updated periodically to account for temperature variations throughout the orbit. Most thermal-structrual analyses of large space structures neglect the dynamics effects in Eq. (4) to use a quasistatic response analysis defined by

$$[K]\{u\} = \{F_T(t)\} \tag{5}$$

and perform a sequence of static analyses at selected points in the transient thermal response The solution of Eq. (5) requires significantly less computational effort than the solution of Eq. (4) and is a permissible approximation, provided that thermally induced oscillations do not occur. Thermally induced oscillations and coupled thermal-structural analyses will be discussed in the next section.

To illustrate characteristics of the structural response of a large space structure, typical deformations of a 43-m diam parabolic tetrahedral truss (Fig. 9) are shown in Figs. 10 and 11. The transient thermal-structural response was computed quasistatically[13] for the 109-node, 420-element truss in GEO using the temperature histories shown in Fig. 7.

Structural response may be characterized by the change in diameter of the truss, by a shear deformation between the faces, and by out-of-plane distortions of the faces. Figure 10 shows the change in diameter of the diagonal of the parabolic truss in GEO. The change in diameter follows the temperature histories in Fig. 7. Figure 11 presents the shear deformation of the parabolic truss. The shearing deformation is computed from the displacements u_1 and u_2 of two joints (Fig. 11), and the two faces of the truss shear with respect to each other because of changes in length of the core members. As the faces of the parabolic truss shear, they experience an out-of-plane distortion. The maximum normal nodal displacement was about 1 mm; the maximum root mean square (RMS) out-of-plane distortion was 0.6 mm. In contrast, a flat truss exhibits no out-of-plane surface distortion. As the structure orbits, the deformation of the core members causes the faces to shear with respect to each other, but the faces remain perfectly flat. These results are based on temperatures computed by neglecting member-to-member shadowing effects.

An elementary sensitivity analysis[36] for a flat tetrahedral truss in GEO shows that the RMS error in the diameter change expressed as a ratio ω_D is

$$\omega_D = \left[\omega_\alpha^2 + \frac{1}{4}\left(\omega_a^2 + \omega_\epsilon^2\right)\right]^{1/2} \tag{6}$$

where ω_α is the error in the CTE, ω_a is the error in absorptivity, and ω_ϵ is the error in the emissivity. Equation (6) shows that for equal errors in the parameters the CTE error is the dominant parameter. For a 10% error in each parameter, the error in the computed deformation is about 12%, which demonstrates the dominance of the CTE. There is a need for additional, more sophisticated sensitivity analyses to assess material property changes on space structures' performance.

Thermally Induced Vibrations

Thermally induced vibrations of beams and plates were studied by classical analytical methods in the 1950s.[37] The studies showed that structural inertia assumes importance only in exceptional cases, and that for most analyses, inertia effects may be disregarded to permit quasistatic, thermal-structural analyses. Very thin beams and flat plates were the exceptions. For these structural components, thermal shock introduced structural vibrations with amplitudes up to twice the corresponding quasistatic deflection.

Thermally induced vibrations of space structures became known during the flight of the OGO-IV spacecraft in the 1960s. On that flight a 18-m (60-ft) experiment boom sustained a solar-induced large amplitude oscillation which severely compromised spacecraft performance. A detailed study of the problem[38] showed that a coupled thermal-structural analysis predicted thermally induced, torsional-flexural vibrations consistent with the observed phenomena. The study showed that the thermally induced vibrations could be eliminated by increasing the boom torsional rigidity. Flight data for later satellites support this conclusion.

Although large space structures have potential for thermally induced oscillations,[39,40] there is little on-going research in this area, particularly on large, complex systems.

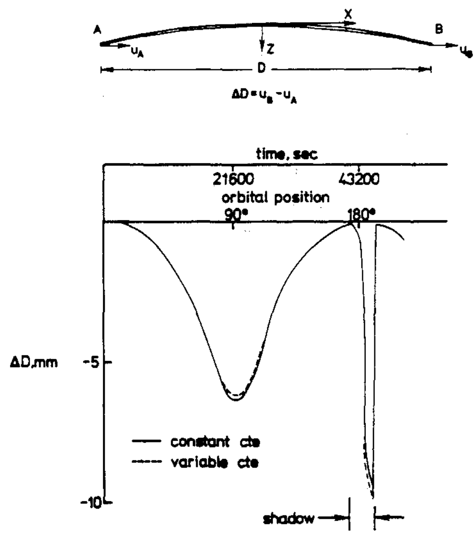

Fig. 11 Truss shearing deformation history.[13]

Computer Programs

The authors' industry visits have determined that there is a strong industry trend to perform the heating and thermal analysis by finite difference-lumped-parameter programs and to perform structural analysis by finite element programs. The results of an informal survey (Table 2) show programs used by companies active in large space structure design and development.

Descriptions of most of the heating and thermal analysis programs appear in Refs. 41-43. The predominant heating analysis program is the Thermal Radiation Analyzer System (TRASYS). Reference 44 describes recent developments in TRASYS. TRASYS has been used extensively for U.S. spacecraft radiation heat transfer analysis since 1972. The output of the program is lumped parameter nodal data formatted for direct interface with a thermal analyzer such as MITAS or CINDA. The principal program output is radiation conductors and total heating as a function of time. The MITAS-CINDA lumped-parameter, finite-difference programs (Ref. 41) are used predominantly for the conduction-radiation thermal analysis of spacecraft. MSC-NASTRAN is the most widely used finite-element structural analysis program.

Because of differences in thermal and structural models and the associated computer programs, there is widespread industry interest in more effective methods of interfacing these analyses. There is also interest in further automating the thermal-structural design cycle through the use of geometric models such as used in Computer Aided Design and employing sophisticated computer graphics programs. The

Table 2 Computer programs used in large space structures thermal-structural analysis

	Analysis		
Company	Heating	Thermal	Structural
Harris Corporation	TRASYS	MITAS	MSC-NASTRAN
Martin Marietta	TRASYS	MITAS	MSC-NASTRAN ANSYS
General Dynamics	TRASYS	QIPETA[a]	MSC-NASTRAN
Rockwell	TRASYS	CINDA	NASTRAN (MSC and Cosmic)
TRW	TRASYS	TAP[a]	MSC NASTRAN SAAS
Lockheed	TRASYS	THERM[a] SINDA HEATRATE[a] NEVADA SPAR	SPAR NEPSAP

[a] Proprietary program.

automation of the thermal-structural design cycle has not been accomplished in most companies, but there are efforts toward this goal underway at NASA. The Integrated Analysis Capability (IAC)[45] is one example. The IAC effort is devoted to integrating interdisciplinary codes. It consists of new software that accelerates interdisciplinary data flow by maximizing use of modern data handling techniques and new generation computer systems. Other examples are LASS[10,11] and IDEAS.[46-47] A unique feature of these programs is the use of a common geometric model for all analyses. Other examples include finite element thermal-structural analysis programs that have both thermal and structural analysis capability. The most well known of these is NASTRAN (see Ref. 48 for a recent review of NASTRAN thermal analysis capability). A less well known but modern thermal-structural analysis program is SPAR.[49] The SPAR thermal analyzer is a modular, interactive data-base type program for general heat transfer analysis that interfaces with a similar structural analysis program.

Concluding Remarks

This paper reviews recent advances in thermal-structural analysis of large space structures. A NASA design for a microwave radiometer system is used to illustrate characteristics of a large space structure design. Large space structures' heating, thermal, and structural analysis methods are also reviewed. Typical analytical modeling techniques and response characteristics are discussed and illustrated for tetrahedral trusses. Uncertainties in thermal-structural analysis methods are highlighted. Computer programs used in research and design are identified and discussed.

Important areas for thermal-structural research that were identified include: 1) spacecraft self-shadowing effects on structural response; 2) effects of large prime-power systems on spacecraft thermal-structural behavior; 3) better knowledge of material properties and their effects on long-term structural response; 4) improved computer program capability to model and analyze nonlinear pretensioned structural components; and 5) better understanding of thermally induced structural vibrations. Additional computations with large structures are needed to delineate problems further because computations with preliminary structural designs have only partially identified problems in analysis capabilities. Additional computations should be performed with better-defined structures with realistic properties and heat loads. There is widespread industry interest in more effective methods of interfacing and automating the interdisciplinary analyses. Finally, many of the uncertainties will be resolved only through the interplay of analysis and experiment. There is a definite need for fundamental thermal-structural experiments to validate thermal-structural analysis of large space structures.

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