FINITE ELEMENT THERMAL-STRUCTURAL MODELING OF ORBITING TRUSS STRUCTURES

Earl A. Thornton, Associate Professor
Jack Mahaney, Undergraduate Research Assistant
Pramote Dechaumphai, Graduate Research Assistant

Mechanical Engineering and Mechanics Department
Old Dominion University
Norfolk, Virginia 23508

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INTRODUCTION

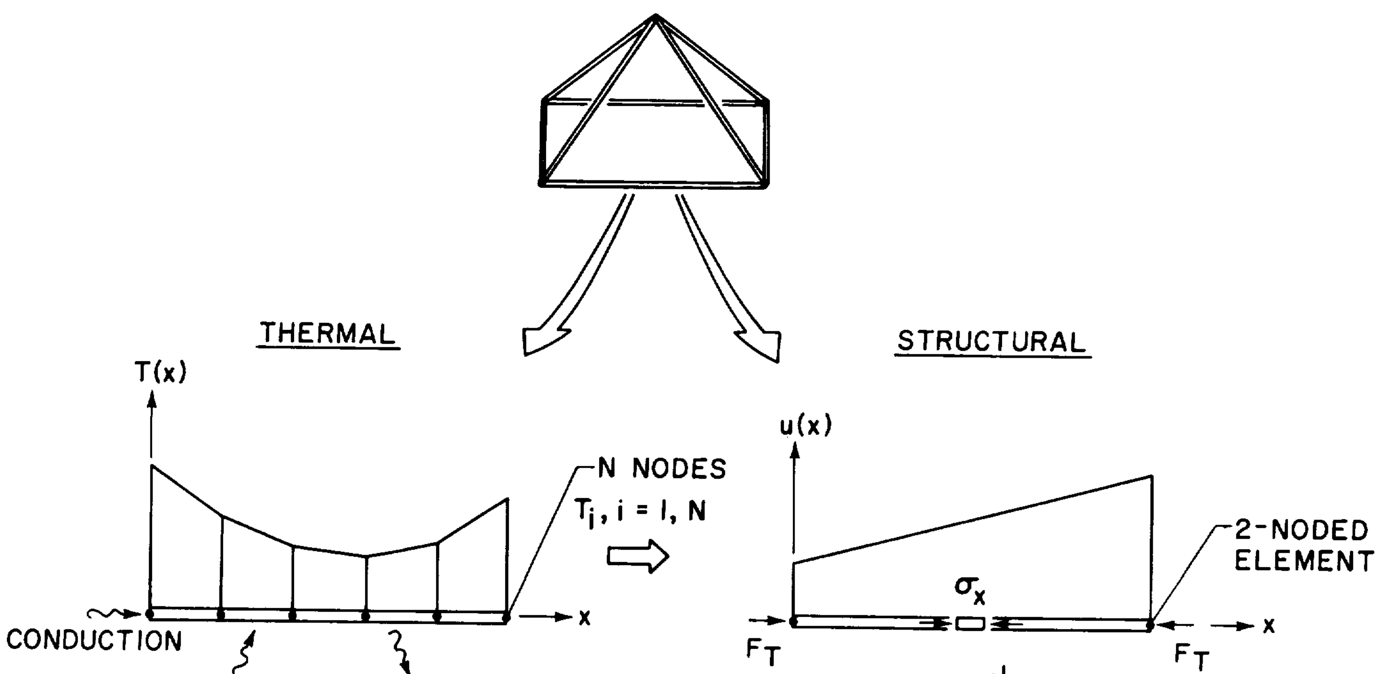
The flights of Columbia have given added impetus to large space structures research. In the next few years large orbiting structures will be deployed or constructed in orbit. One structural concept under development at the NASA-Langley Research Center is the tetrahedral truss. The large size of these trusses and stringent operational requirements for allowable deformations have placed emphasis on effective analysis methods. The purpose of this paper is to describe an integrated finite element (FE) thermal-structural approach for accurate and efficient modeling of large space structures.

The paper will first describe differences between the conventional FE approach as implemented in large programs and an integrated FE approach currently under development (refs. 1-3). Considerations for thermal modeling of truss members will be discussed next, and three thermal truss finite elements will be presented. The performance of these elements will then be evaluated for typical truss members neglecting joint effects. Finally, a simple truss with metallic joints and composite members will be studied to evaluate the effectiveness of the approach for realistic truss designs.

- MOTIVATION
  - SIZE OF STRUCTURES
  - ACCURATE PREDICTION OF HEAT LOADS AND TEMPERATURE
  - CONTROL OF DEFORMATION
- PURPOSE
  - DESCRIBE INTEGRATED FINITE ELEMENT (FE) THERMAL-STRUCTURAL MODELING OF LARGE SPACE TRUSSES
- SCOPE
  - CHARACTERISTICS OF INTEGRATED APPROACH
  - ORBITING STRUCTURES THERMAL MODELING
  - DESCRIPTION AND COMPARISON OF FINITE ELEMENTS
  - CONDUCTANCE EFFECTS ON TEMPERATURES
  - JOINT EFFECTS ON TEMPERATURES AND DEFORMATIONS

CONVENTIONAL THERMAL-STRUCTURAL TRUSS ANALYSIS

In orbit, a truss member experiences a nonlinear temperature distribution due to the combined heat transfer modes. Typically, there are significant temperature gradients near the joints and interior temperatures may be higher or lower than the joint temperatures. To represent this temperature distribution, several conventional two node finite elements based on a linear temperature variation are required. Additionally, different thermal-structural models are required since a single conventional two-node element can be used for the structural analysis. Since most programs compute only nodal temperatures, T_i, integration of the member temperature distribution is required between analyses to obtain the equivalent nodal forces for the structural analysis. Thus, use of conventional finite element programs such as NASTRAN and SPAR for thermal-structural analysis of orbiting trusses leads to different thermal-structural models and requires extra data processing between the thermal and structural analyses.

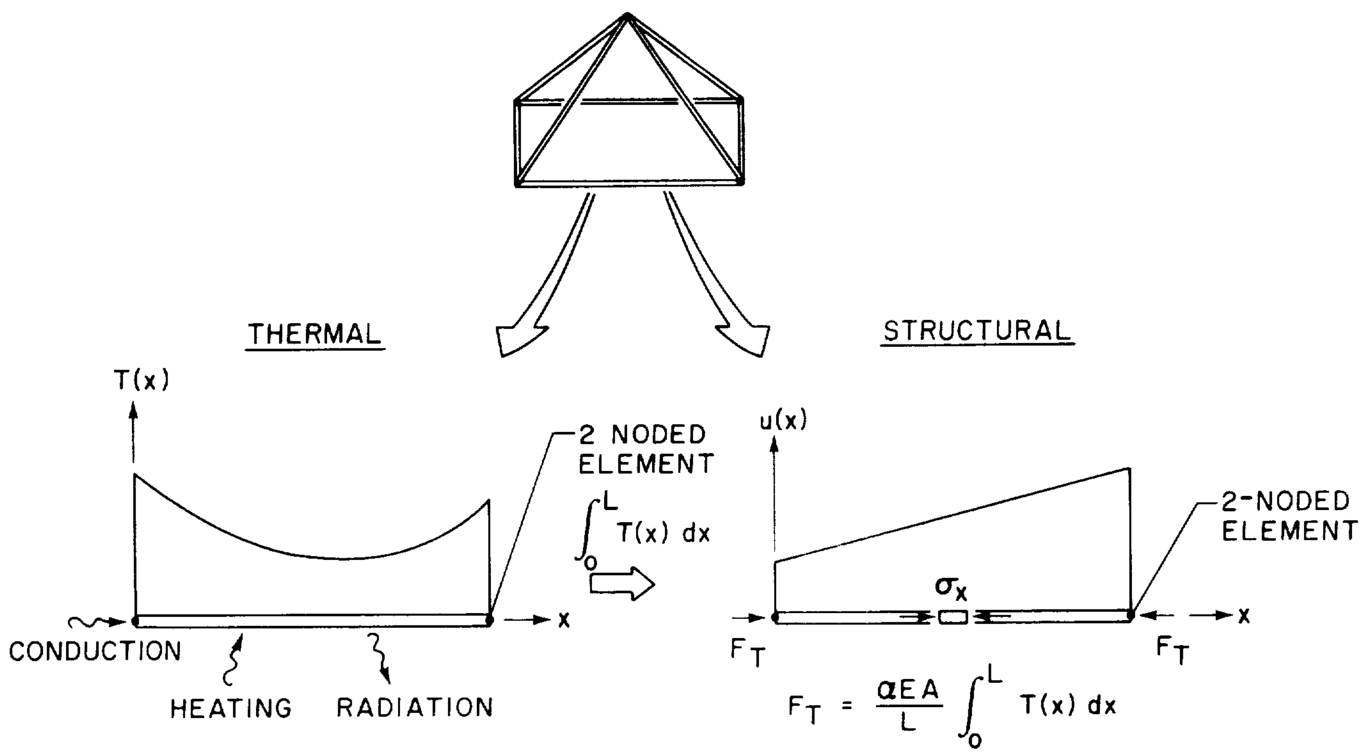


$$F_T = \frac{\alpha E A}{L} \int_0^L T(x)\, dx$$

- DIFFERENT THERMAL-STRUCTURAL MODELS
- T(x) INTEGRATION REQUIRED BETWEEN ANALYSES

INTEGRATED THERMAL-STRUCTURAL TRUSS ANALYSIS

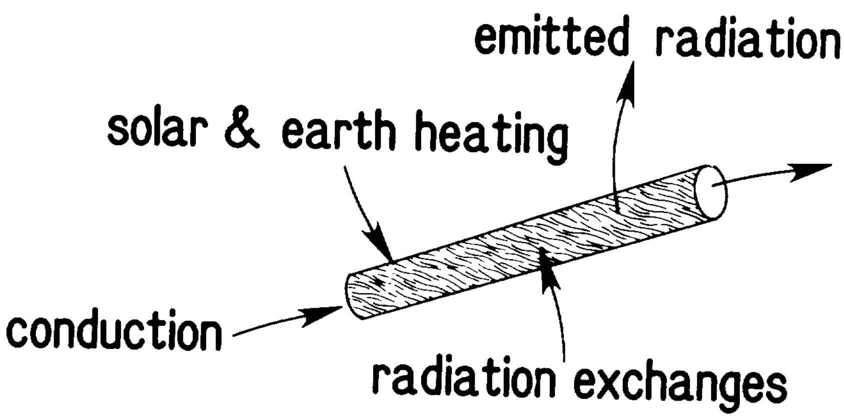
The purpose of the integrated thermal-structural analysis approach is to improve the accuracy and efficiency of the combined analyses. Improvement in accuracy (for comparable number of unknowns) is obtained by using improved thermal elements to represent member nonlinear temperature distributions. The improved thermal elements are formulated with two nodes to permit a common discretization for thermal and structural models. Later figures will show that the type of thermal element required depends on the thermal properties of the member. After temperatures are computed, the member temperature distribution is integrated within the thermal analysis program and transferred directly to the structural program. Thus the thermal and structural models use a common discretization with no data processing required between analyses. Observe that although a common discretization (i.e. common nodes and element connections) is used, the mathematical formulation of the thermal and structural elements are different. This is an important distinction between the conventional and integrated approaches, and the different formulation of the elements in the integrated approach is the basis for improvement in accuracy and efficiency.



- SAME DISCRETIZATION
- NO DATA PROCESSING REQUIRED BETWEEN ANALYSES

ORBITING STRUCTURES THERMAL MODELING

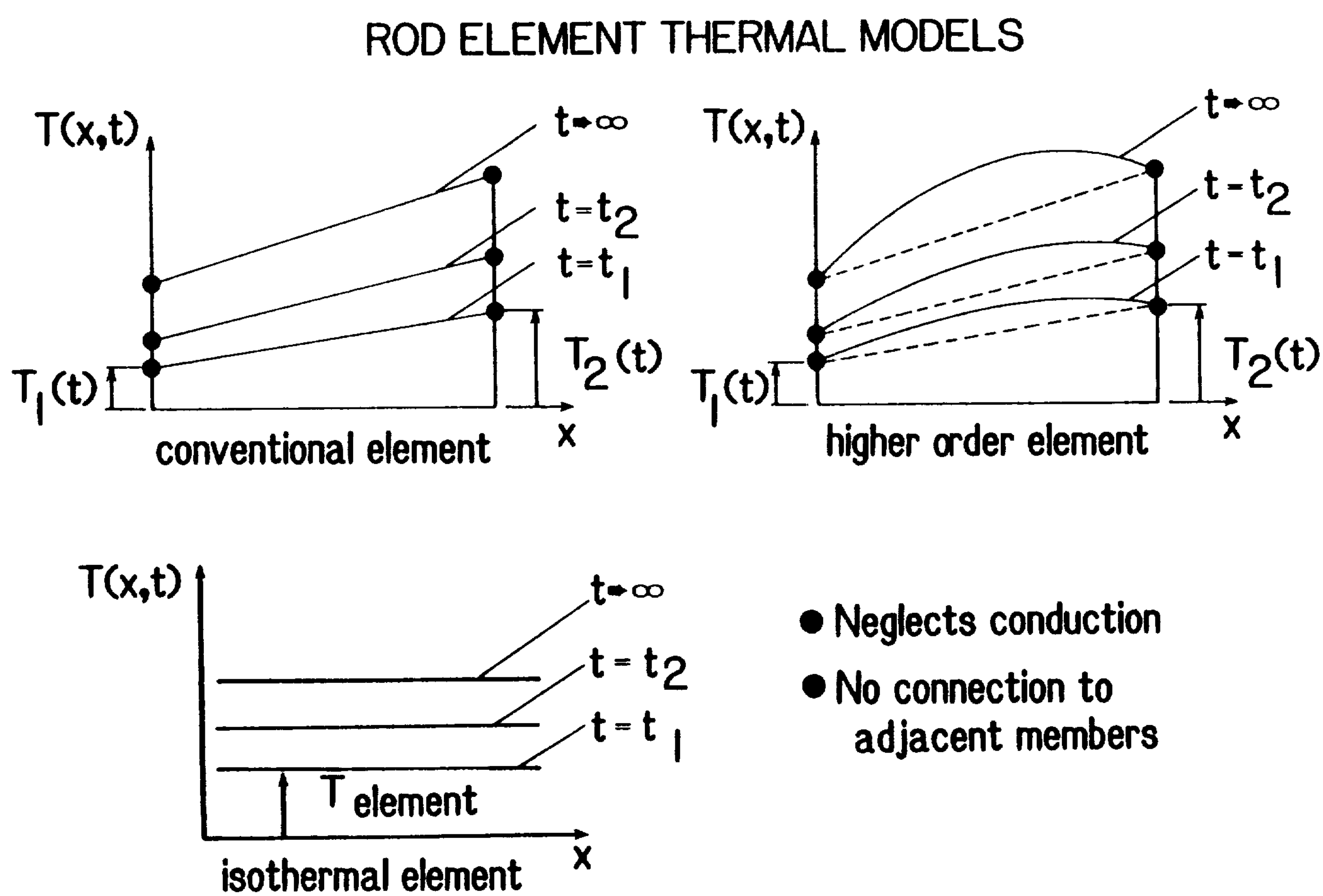
A truss member experiences conduction heat transfer combined with emitted radiation and radiation heating from both nearby truss members and other satellite components. In this study of fundamental concepts of thermal-structural modeling, a number of simplifying assumptions are made. Radiation exchanges between members are neglected because computational experience (ref. 4) has shown that the member-to-member radiation heat exchanges in a truss are negligible in comparison to 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, but, herein, member properties are assumed constant. Member-to-member shadowing effects may also be significant, but they are not considered. Temperature gradients through the member thickness are likewise neglected so that the temperature is assumed to vary only along the member length. The basic heat transfer problem is inherently nonlinear because of the emitted radiation and transient because of the strong time-dependence of the heat loads. Heat load computations are described briefly in Reference 3.



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

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.



EFFECTS STUDIED

To evaluate the three thermal finite elements, studies were made to determine: (1) the effect of thermal conductance on temperature distributions, and (2) the effects of metallic joints on temperatures and displacements for composite members. The studies were performed by first computing detailed temperature distributions for a three-member truss with a refined model of conventional elements. Then, the performance of each thermal element was evaluated by comparing one element per member solutions with the refined model results.

A truss member temperature distribution depends on the member conductance kA/L where k is the thermal conductivity, A is the cross-sectional area and L is the member length. Two cases of conductance are considered: high conductance, which is characteristic of metallic members, and low conductance, which is characteristic of composite members. In this study member joints are neglected.

In the second study, modeling of composite members with metallic joints was considered. Both the thermal and deformation response are computed, and an approximate method for including metallic joint effects in simple finite element models is presented.

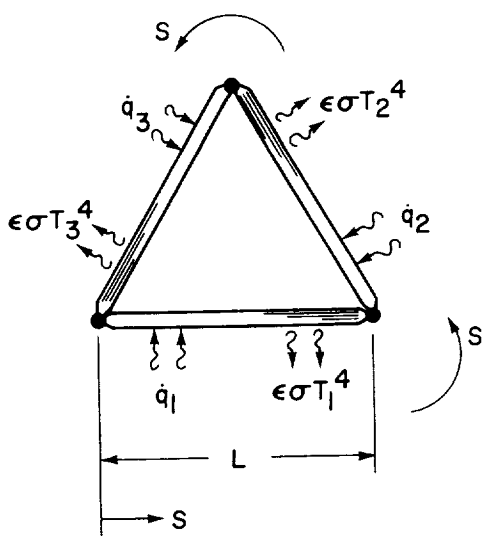
- THERMAL CONDUCTANCE (KA/L) ON TEMPERATURES
  - NEGLECT JOINTS
  - HIGH CONDUCTANCE MEMBERS (METALLICS)
  - LOW CONDUCTANCE MEMBERS (COMPOSITES)

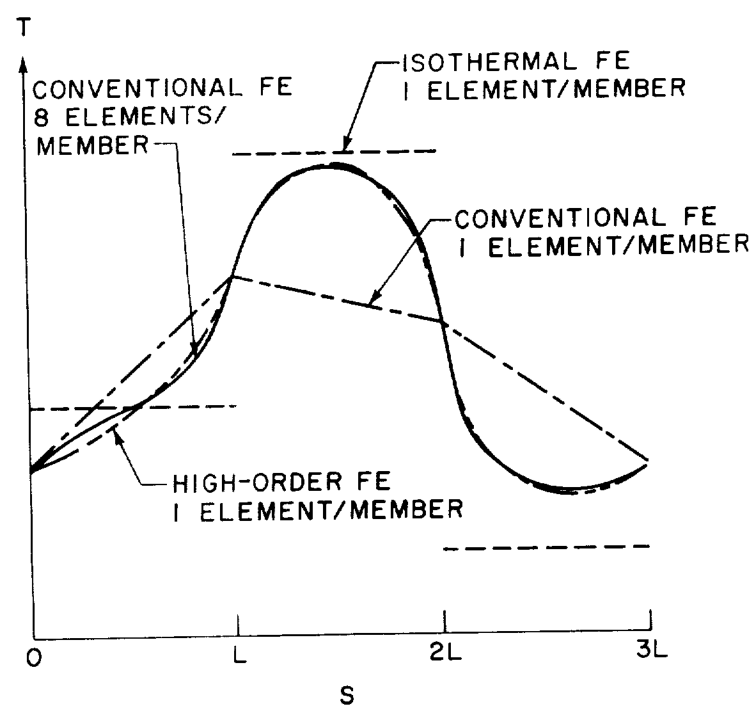
- METALLIC JOINTS WITH COMPOSITE MEMBERS
  - TEMPERATURE RESPONSE
  - DEFORMATIONS
  - APPROXIMATE ANALYSIS APPROACH

HIGH CONDUCTANCE TRUSS MEMBER TEMPERATURE DISTRIBUTIONS

The simple three-member truss shown is subject to different heating rates and undergoes steady-state heat transfer. Each member of the truss was first modeled with eight conventional elements, and the computed temperatures (shown as the solid line) serves as the reference "exact" solution for the evaluation. Member conductance was based on all aluminum members. The truss was then analyzed with: (1) one conventional element per member, (2) one higher-order nodeless variable element per member, and (3) one isothermal element per member.

The figure shows that one conventional element per member predicts the nodal temperatures quite well but either under- or overestimates interior member temperatures. Since member forces depend on the integration of member temperature distributions, use of a single conventional element per member introduces serious errors in the structural analysis and is not recommended. The isothermal element predicts neither accurate nodal temperature nor average member temperatures and is clearly inadequate. The single nodeless variable element per member does an excellent job of predicting the nodal and member interior temperatures and is the superior element for this high conductance case.



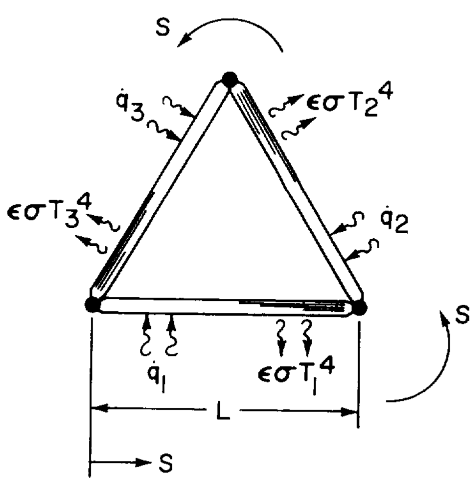


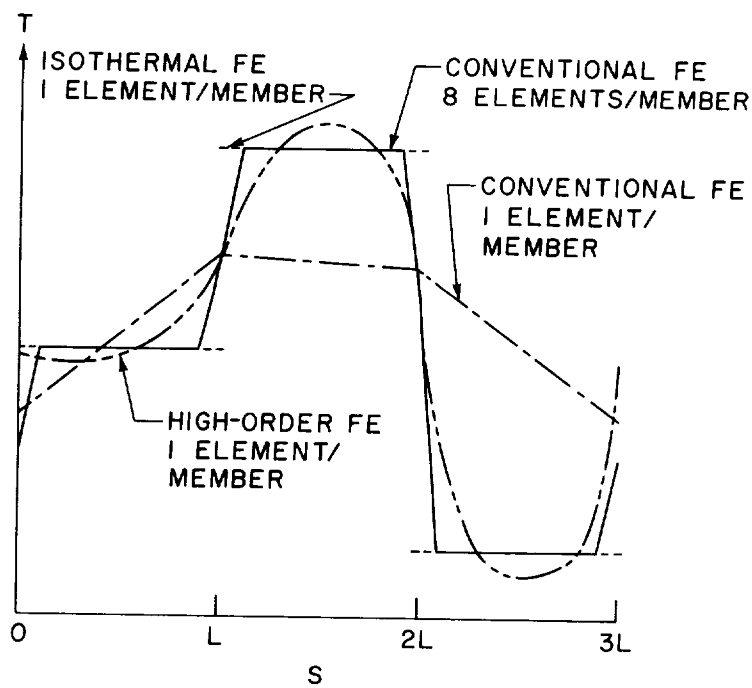
LOW CONDUCTANCE TRUSS MEMBER TEMPERATURE DISTRIBUTIONS

The three-member truss in the previous figure was re-analyzed with a conductance based on all graphite-epoxy members.

The "exact" solution based on eight conventional elements per member shows extremely sharp temperature gradients near the joints but nearly uniform temperature over most of the member length. 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. The higher-order element did better than the single conventional element but tended to under- or overestimate member interior temperatures.

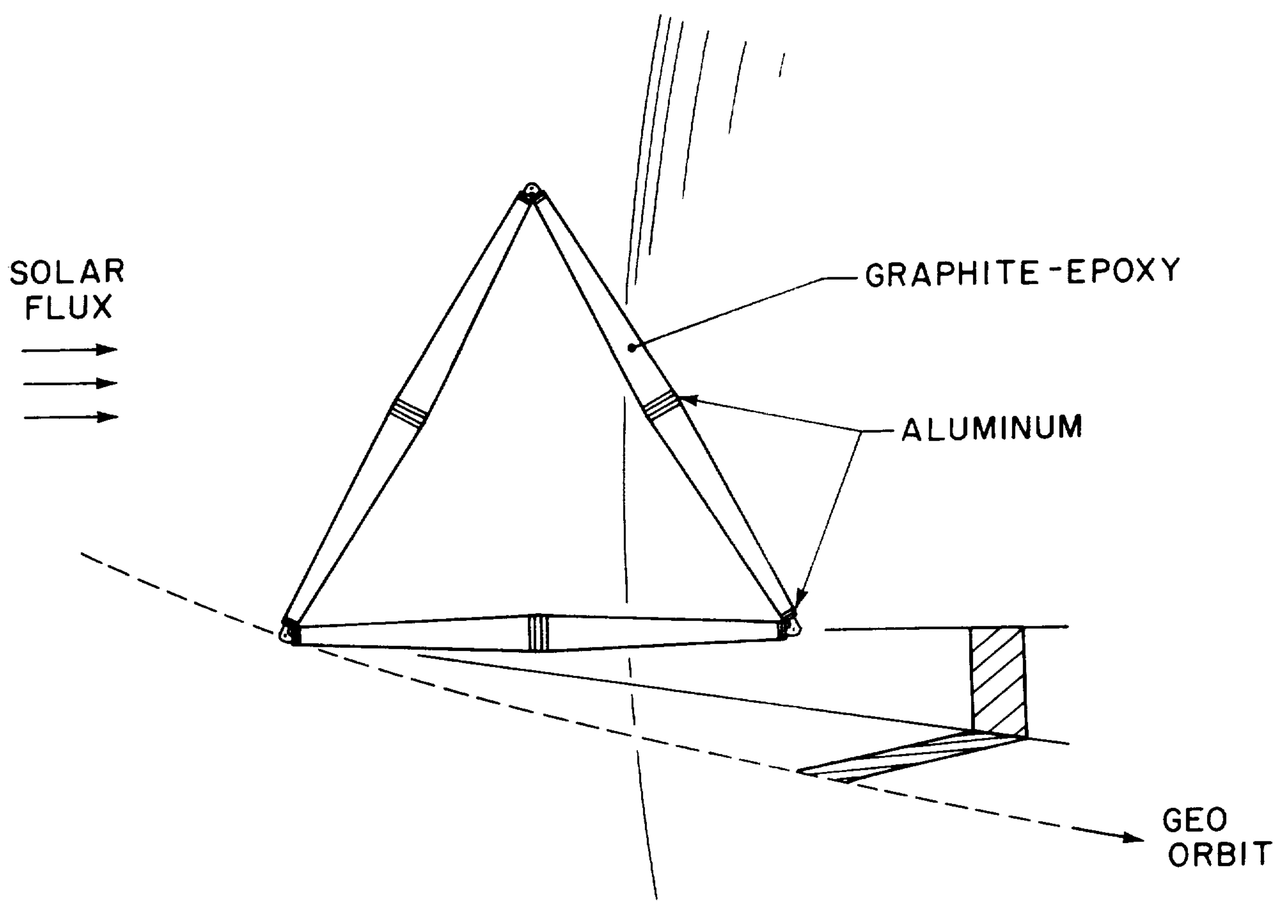
For computation of the structural response, the results from the isothermal elements are superior for this low conductivity material since the average member temperature is predicted quite well. Use of these elements gives improved structural accuracy and also allows smaller, uncoupled thermal models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





THREE-MEMBER ORBITING TRUSS USED IN JOINT EFFECTS STUDY

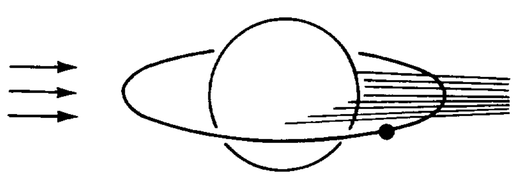
The previous figure showed that one isothermal element per member was capable of predicting member temperatures of graphite-epoxy members. To investigate the effects of metallic joints, a three-member truss based on the LRC octetruss, ref. 5, was analyzed. Each member consists of two truncated cones made of graphite-epoxy tubes connected with aluminum joints and is 5.42 meters (213 inches) long from end to end. The transient thermal-structural response was computed for the truss in a geosynchronous orbit in the ecliptic plane. The truss is earth-facing, but the truss plane is oriented obliquely so that each member receives different solar heating.

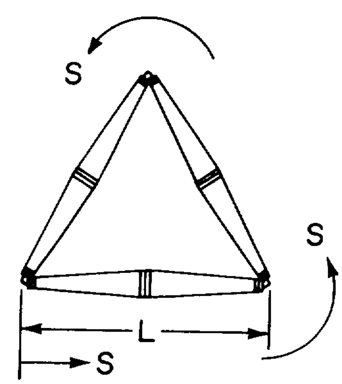


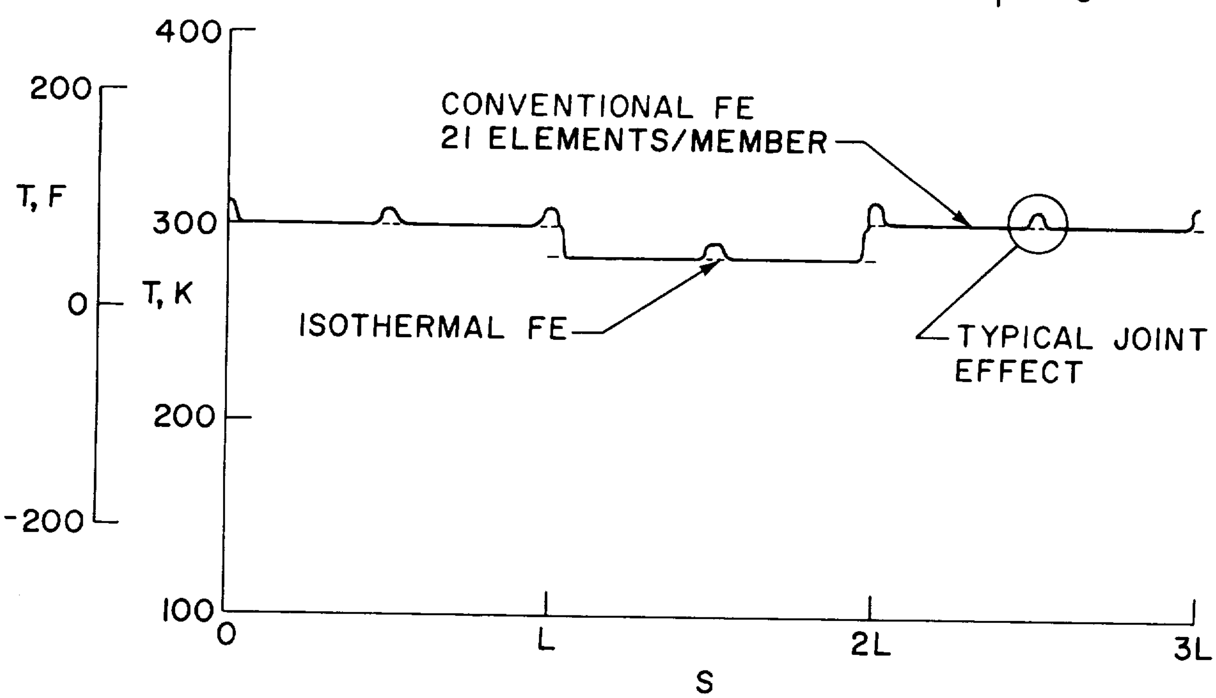
TRUSS TEMPERATURE DISTRIBUTIONS AT TYPICAL ORBIT POSITION

The truss is shown receiving solar heating at a typical orbit position prior to entering the earth's shadow. Truss temperatures were computed using a detailed model of twenty-one conventional elements per member taking into account the different thermal properties of the aluminum and graphite-epoxy members and varying cross-sectional area. Temperatures were also computed with one isothermal element per member neglecting the joints.

For this typical orbit with direct solar heating, joint effects are small. Member temperatures are nearly uniform except the joints have slightly higher temperatures due to different surface properties. All temperatures are very close to radiation equilibrium; surface absorptiveness and emittance control the temperatures. Member temperatures are predicted quite well by a single isothermal element per member.



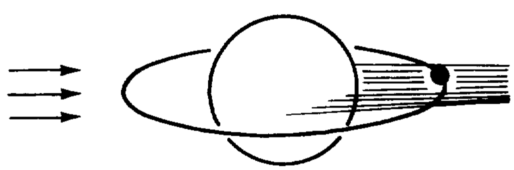


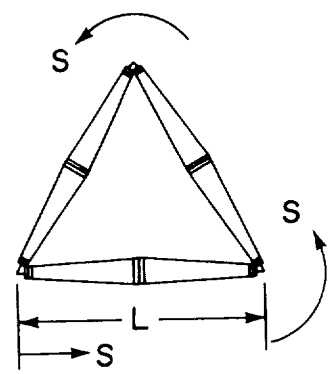


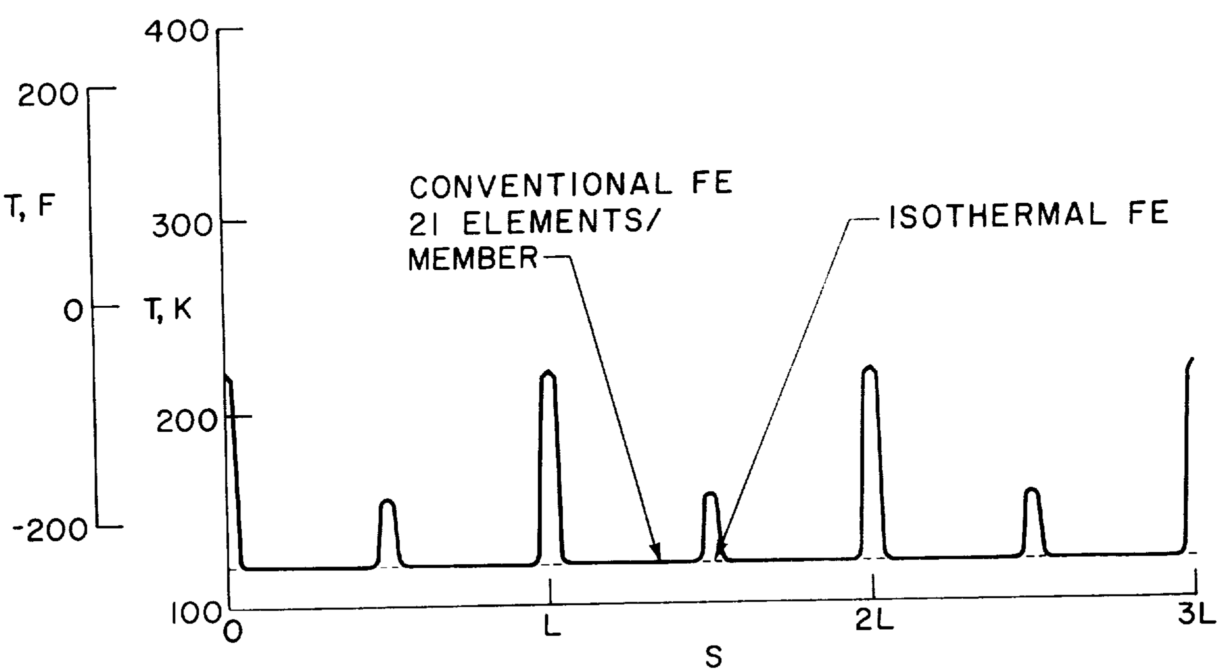
TRUSS TEMPERATURE DISTRIBUTIONS IN EARTH SHADOW

Once the truss enters the earth shadow, there is a rapid drop in temperatures since the only incident heating is due to earth emission, which is quite small. The composite member temperatures drop quite rapidly, but the joint temperatures fall more slowly due to their larger thermal capacitance which controls the transient thermal response. Thermal capacitance is defined as ρcV where ρ is the density, c is the specific heat, and V is volume.

Member temperatures are equal due to the small earth heating and are predicted accurately by the isothermal elements.



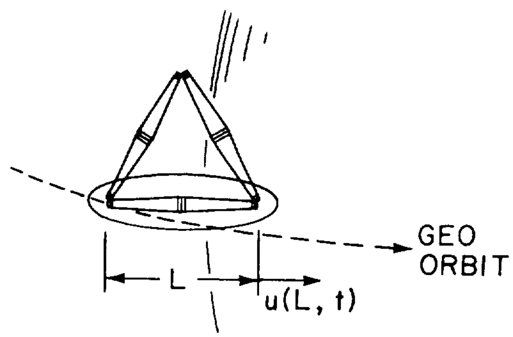


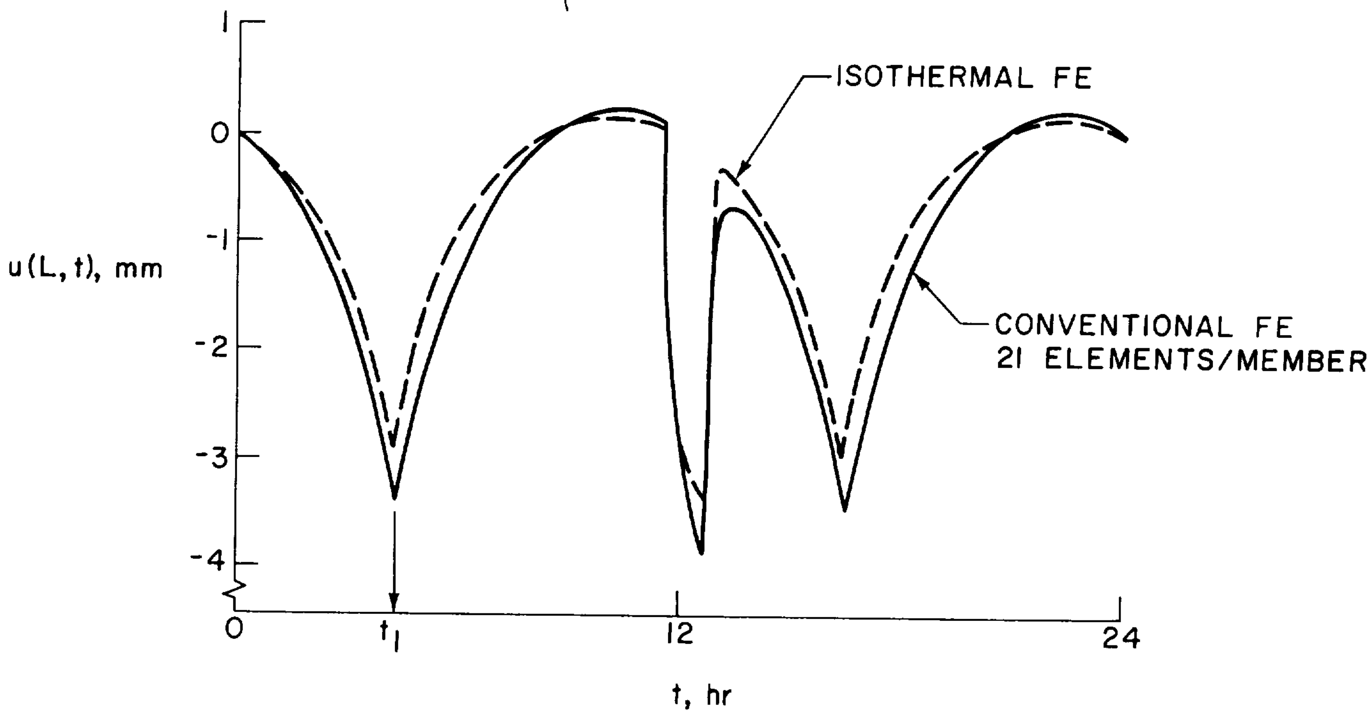


TRUSS MEMBER AXIAL DISPLACEMENT ORBITAL HISTORY

The axial displacement history of a typical truss member is shown during a geosynchronous orbit period. Deformations are based on a noon position reference temperature when the member receives large solar heating. The member first contracts and then expands slightly during the first twelve hours of the orbit as the incident heat drops and then rises with changing member orientation. The member lies in an oblique earth-facing plane and receives maximum solar heating at t = 11 hours when the small thermal expansion occurs. During earth shadow transit there is a rapid contraction of the truss, and it experiences its maximum distortion.

The structural response based on the isothermal element temperature history and a single structural element with only the graphite-epoxy coefficient of expansion tends to underestimate the structural deformations. The next figure shows the variation of the axial displacement along the member length at time $t = t_1$ on the graph below.



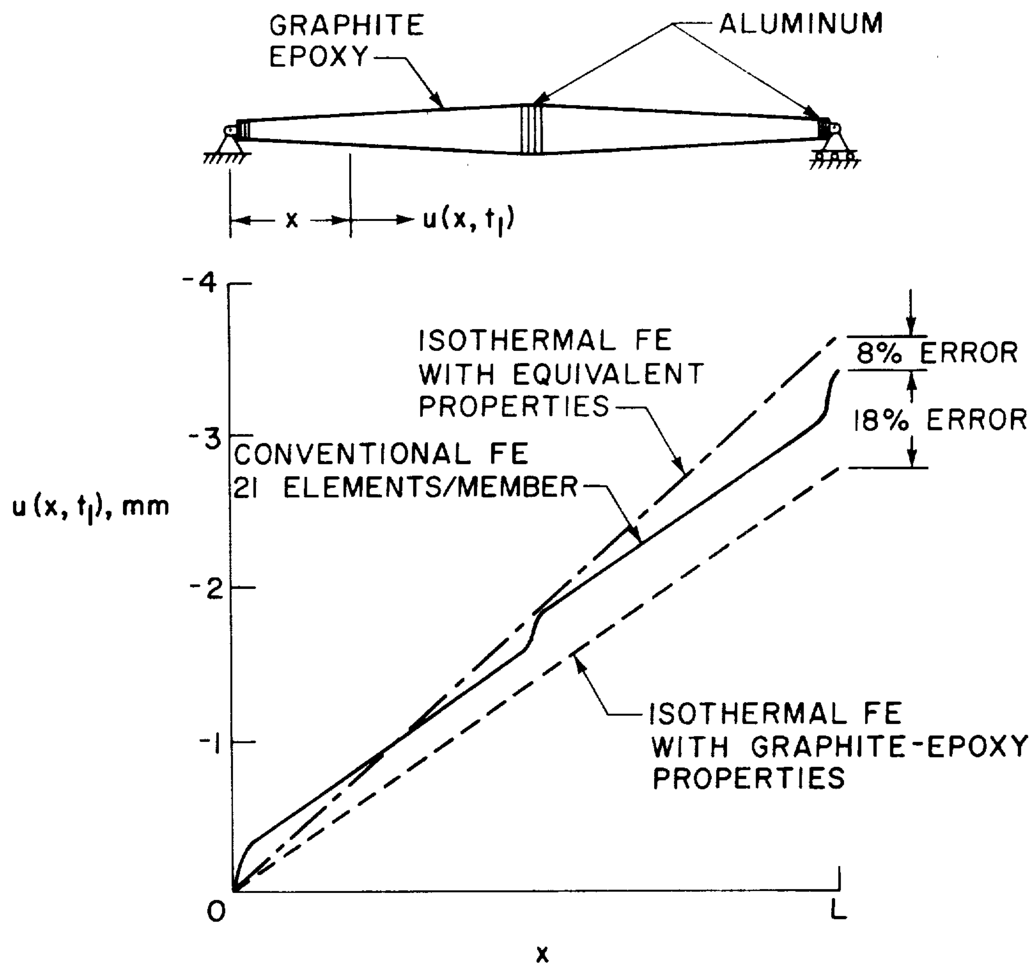


TRUSS MEMBER AXIAL DISPLACEMENT DISTRIBUTIONS

The details of the axial displacement variation along member length is shown at time $t = t_1$. The conventional twenty-one element solution shows the relatively larger distortions experienced by the member at the three aluminum joints due to their higher thermal expansion coefficients. As mentioned previously, a single structural element with only the graphite-epoxy coefficient of expansion underestimates the deformation since it neglects the aluminum joints; maximum member contraction is underestimated by 18 percent.

To compensate for the aluminum joints, another isothermal analysis was performed with equivalent member capacitances and thermal expansion coefficients based on weighted averages of member aluminum and graphite-epoxy properties. This analysis overestimated the member contraction by 8 percent.

There are significant computational savings to be gained by using one isothermal element and one structural element per truss member. In a large truss with hundreds of members, the one element per member approach is probably the only tractable solution method. The above study shows, however, that aluminum joints can have significant effects on deformations. Additional study is needed to define clearly the role of joint effects of deformations of large trusses.



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 uses improved thermal elements and the results from the thermal analysis directly in the structural analysis without any intervening data processing.

Comparative calculations for three thermal elements show that a higher-order element works best for high conductivity materials and that an isothermal element works best for low-thermal conductivity materials. These elements give a good representation of member temperatures and yield the best member forces. Conventional two-node elements available in NASTRAN and SPAR predict temperatures well in a refined mesh with several elements per member, but they would not be effective in large truss analysis due to prohibitive computational costs. Analyses with isothermal elements would be preferable for trusses with composite members since member temperatures can be computed efficiently and accurately.

A study of the effects of aluminum joints on the thermal deformations of a simple, plane truss with composite members showed that joint effects may be significant. When aluminum joints were neglected, member deformations were underestimated by 18 percent. Further study is needed to assess the role of joint effects on the deformation of large trusses.

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- 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
- CONVENTIONAL THERMAL ELEMENTS IN NASTRAN AND SPAR NOT EFFECTIVE
- METALLIC JOINT EFFECTS SIGNIFICANT AND REQUIRE FURTHER STUDY
- INTEGRATED FINITE ELEMENT APPROACH ATTRACTIVE FOR ORBITING STRUCTURES ANALYSIS

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, pp. 957-999, AIAA Paper No. 80-0717.

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, pp. 16-32, AIAA Paper No. 81-0480.

3. Mahaney, Jack; Thornton, Earl A.; and Dechaumphai, Pramote: Integrated Thermal-Structural Analysis of Large Space Structures. Symposium of Computational Aspects of Heat Transfer in Structures held at NASA Langley Research Center, November 3-5, 1981. (To be published as a NASA CP.)

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

5. Card, M. F.; Bush, H. G.; Heard, W. L., Jr.; Mikulas, M. M., Jr.: Efficient Concepts for Large Erectable Space Structures. Large Space Systems Technology, An Industry/Government Seminar held at NASA-Langley Research Center, Hampton, Virginia, January 17-19, 1978. NASA CP 2035, pp. 627-656.