# Design of a Carbon Fiber Composite Grid Structure for the GLAST Spacecraft Using a Novel Manufacturing Technique* 

Michael Thomas Hicks<br>Stanford Linear Accelerator Center<br>Stanford University<br>Stanford, CA 94309

SLAC-Report-575
June 2001

Prepared for the Department of Energy
under contract number DE-AC03-76SF00515

Printed in the United States of America. Available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

[^0]
# Design of a Carbon Fiber Composite Grid Structure for the GLAST Spacecraft Using a Novel Manufacturing Technique 

A DISSERTATION<br>SUBMITTED TO THE DEPARTMENT OF AERONAUTICAL AND ASTRONAUTICAL ENGINEERING<br>AND THE COMMITTEE ON GRADUATE STUDIES<br>OF STANFORD UNIVERSITY<br>IN PARTIAL FULFILLMENT OF THE REQUIREMENTS<br>FOR THE DEGREE OF<br>DOCTOR OF PHILOSOPHY

Michael Thomas Hicks
June 2001

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Stephen W. Tsai<br>(Principal Advisor)

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Elliott Bloom

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

George S. Springer

Approved for the University Committee on Graduate Studies:

## ABSTRACT

The Gamma-Ray Large Area Space Telescope is an orbital observatory being planned as a joint DOE/NASA mission. The primary support of the instrument requires a grid structure which is very stiff, strong, light-weight, and thermally conductive. A carbon fiber composite grid design using a novel manufacture technique is proposed which meets or exceeds an aluminum design in all performance criteria and is economically competitive as well. Finite element analysis, confirmed by testing of a sample grid, is used to examine trade-offs for the materials and layups. Based on these analyses, recommendations are given for a viable design.

## ACKNOWLEDGMENTS

This work was sponsored by the Department of Energy through the Stanford Linear Accelerator Center's Experimental Group K. I would like to thank all those working on the GLAST project for their support, and for the opportunity to work on so many aspects of such an interesting problem. Specifically, I would like to acknowledge Professor Elliott Bloom for championing the use of carbon composites in the GLAST program, and for generously funding my efforts.

I would like to thank my advisor, Professor Stephen Tsai, for his guidance and the breadth of experience I was able to gain working on this thesis works and the other projects which preceded it. I would truly like to thank the members of the Structures and Composites Laboratory; the professors and visiting scholars for their constructive criticism and for not letting me get away with anything, and Julie Wang and my fellow students for so many hours of help, advice, and camaraderie.

I am especially grateful for my family and so many close friends who have collectively maintained my sanity and made these past seven years so much more fun than they were supposed to be. And finally, thank you Kourtny, for being my beacon ...

## Table of Contents

LIST OF FIGURES ..... ix
LIST OF TABLES ..... xi
CHAPTER 1: INTRODUCTION ..... 1
1.1 GLAST MISSION ..... 1
1.2 GLAST INSTRUMENT DESIGN AND OPERATION ..... 1
1.3 GRID DESIGN PROBLEM ..... 4
1.4 COMPOSITE MATERIALS VS ALUMINUM ..... 6
1.5 PROBLEM STATEMENT ..... 8
1.6 THESIS CONTRIBUTION ..... 8
CHAPTER 2: MANUFACTURE METHOD ..... 10
2.1 INTRODUCTION ..... 10
2.2 OTHER MANUFACTURE METHODS ..... 10
2.2.1 SLOTTED-JOINT GRID ..... 10
2.2.2 INTERLACE GRID ..... 11
2.2.3 TRIG GRID ..... 12
2.3 SLOTTED-JOINT TRIG METHOD ..... 13
2.3.1 OVERVIEW ..... 13
2.3.2 RIB MANUFACTURE ..... 15
2.3.3 INTERLACE PROCEDURE ..... 18
2.4 DESIGN WITH SLOTTED JOINT TRIG ..... 19
2.5 CONCLUSION ..... 21
CHAPTER 3: DESIGN PROBLEM ..... 22
3.1 INTRODUCTION ..... 22
3.2 DESIGN REQUIREMENTS ..... 22
3.2.1 INTERFACES AND INSTRUMENT ACCOMODATION ..... 22
3.2.2 LAUNCH AND ORBITAL ENVIRONMENT ..... 23
3.3 DESIGN SOLUTION ..... 25
3.3.1 TOWER INTERFACE ..... 25
3.3.2 CALORIMETER INTERFACE ..... 27
3.3.3 SPACECRAFT AND ACD INTERFACE ..... 28
3.3.4 DIMENSIONAL TOLERANCE ..... 31
3.3.5 LOAD, FREQUENCY, AND THERMAL REQUIREMENTS ..... 32
CHAPTER 4: FINITE ELEMENT MODELING ..... 34
4.1 MODELING OVERVIEW. ..... 34
4.1.1 TOOLS AND ELEMENTS ..... 34
4.1.2 ANALYTICAL VALIDATION ..... 35
4.2 FREQUENCY MODEL ..... 42
4.2.1 MODEL FEATURES ..... 42
4.2.2 MODELING TECHNIQUE ..... 42
4.2.3 CONVERGENCE OF THE MODEL ..... 45
4.2.4 BOUNDARY CONDITIONS ..... 47
4.2.5 RESULTS ..... 49
4.3 THERMAL MODEL ..... 54
4.3.1 MODEL FEATURES ..... 54
4.3.2 RESULTS ..... 56
4.4 LOAD MODEL ..... 61
4.4.1 MODEL FEATURES ..... 61
4.4.2 RESULTS ..... 61
CHAPTER 5: EXPERIMENTAL VERIFICATION ..... 64
5.1 SPECIMEN DESIGN ..... 64
5.2 MANUFACTURE ..... 65
5.3 TESTING ..... 65
5.4 RESULTS ..... 68
CHAPTER 6: PROPOSED DESIGN ..... 70
6.1 PARAMETERS ..... 70
6.2 MANUFACTURE ..... 71
6.3 COMPARISON TO ALUMINUM GRID ..... 75
REFERENCES ..... 77
APPENDIX A: FEM CODE ..... 78
A. 1 STIFFNESS ANALYSIS PROGRAM ..... 78
A. 2 FAILURE ANALYSIS PROGRAM...................................................................... 99
A. 3 THERMAL ANALYSIS PROGRAM ................................................................. 119

## LIST OF FIGURES

Figure 1-2 GLAST Instrument Overview ..... 2
Figure 1-3 Required deviations from ideal instrument design ..... 3
Figure 1-4 Tower and calorimeter attachment ..... 5
Figure 1-5 Aluminum baseline design, corner detail ..... 6
Figure 2-1 Manufacture of slotted joint grid ..... 11
Figure 2-2 Manufacture of interlaced grid. ..... 12
Figure 2-3 Manufacture of tooling reinforced integral grid ..... 13
Figure 2-5 Slotted joint TRIG rib slots ..... 14
Figure 2-6 Slotted joint TRIG assembly ..... 14
Figure 2-7 Summary of slotted joint TRIG manufacture ..... 15
Figure 2-8 Three ways to manufacture slotted joint TRIG ribs ..... 16
Figure 2-9 Co-curing slotted joint TRIG rib walls and center using inserts ..... 17
Figure 2-10 Cutting slots in slotted joint TRIG ribs ..... 17
Figure 2-11 Interlacing in a fixture using pegs for fiber tension and alignment ..... 18
Figure 2-12 Design variables for Slotted TRIG ..... 19
Figure 2-13 Factors affecting theoretical bending and shear stiffness in ribs ..... 20
Figure 3-1 Grid interfaces to towers, calorimeters, ACD, and spacecraft ..... 23
Figure 3-2 Tower interface using aluminum flange ..... 26
Figure 3-3 Calorimeter interface using mounting brackets ..... 27
Figure 3-4 Launch vehicle configuration and grid support pattern ..... 28
Figure 3-5 Schematic of spacecraft adapter mounting bosses ..... 29
Figure 3-6 ACD and spacecraft adapter interface uses insertable aluminum bosses ..... 30
Figure 3-7 Rib assembly as modified for aluminum boss design ..... 31
Figure 4-1 Finite element model of GLAST grid structure ..... 34
Figure 4-2 Two modeling steps to find thermal expansion ..... 35
Figure 4-3 FEM stiffness verification model ..... 36
Figure 4-4 FEM thermal conductivity verification model ..... 39
Figure 4-5 FEM thermal expansion verification model ..... 41
Figure 4-6 Diagram of different regions used in finite element modeling of the rib ..... 43
Figure 4-8 Parameters for determining FEM mesh density of ribs ..... 45
Figure 4-9 Delta II payload attach fitting with grid dimensions superimposed ..... 48
Figure 4-10 First natural frequency for various candidate spacecraft adapters for two cases of constraint at mounting points ..... 49
Figure 4-11 Thermal expansion modeling using two models ..... 55
Figure 4-12 Locations of grid heat sources ..... 56
Figure 4-13 Vertical thermal gradient causes concave bowing in aluminum grid ..... 59
Figure 4-14 Strength ratios in the chosen design ..... 63
Figure 5-1 Specimen top view and cross-section ..... 64
Figure 5-2 Experimental verification load cases ..... 65
Figure 5-3 Experimental verification bending test ..... 66
Figure 5-4 Experimental verification compression test ..... 67
Figure 5-5 Load vs displacement curve for in-plane test ..... 68

Figure 6-1 Geometry, materials, and layups for GLAST grid design .............................. 70
Figure 6-2 Layup of ribs
71
Figure 6-3 Modification for attachment of spacecraft adapter mounting bosses............. 72
Figure 6-4 Cutting slots into ribs ..................................................................................... 72
Figure 6-5 Rib assembly with proper slot orientation ..................................................... 73
Figure 6-6 Interlace of top side of grid............................................................................ 74
Figure 6-7 Insertion of aluminum spacecraft adapter mounting bosses .......................... 74
Figure 6-8 Interlace of bottom side of grid...................................................................... 75

## LIST OF TABLES

Table 1-1 Comparison of aluminum and cured composite prepreg properties ..... 7
Table 4-1 Comparison of FEM and analytical stiffness results ..... 37
Table 4-2 Failure properties of cured T300/5208 prepreg ..... 38
Table 4-3 Comparison of FEM and analytical failure results ..... 38
Table 4-4 Thermal properties of aluminum and T300/5208 layups ..... 39
Table 4-5 Comparison of FEM and analytical thermal expansion results ..... 40
Table 4-6 First natural frequency as a function of mesh density ..... 46
Table 4-7 Conductivity and coefficient of thermal expansion for aluminum and composite materials in x and y directions ..... 57
Table 4-8 Maximum $\Delta \mathrm{T}$ (in ${ }^{\circ} \mathrm{C}$ ) across all YS90A grid for different wall thicknesses and combinations of wall and center layups ..... 57
Table 4-9 Maximum $\Delta \mathrm{T}$ (in ${ }^{\circ} \mathrm{C}$ ) across T300/YS90A hybrid grid for four ply thick walls and combinations of wall and center layups ..... 58
Table 4-10 Tower gap expansion (in mm ) in an all YS90A grid for different wall thicknesses and combinations of wall and center layups ..... 60
Table 4-11 First mode frequency, thermal gradient, and thermal expansion of the all YS90A design with walls 6 plies thick ..... 61
Table 6-1 Comparison of predicted performance for composite design, old aluminum design, and current aluminum design ..... 76

## CHAPTER 1: INTRODUCTION

### 1.1 GLAST MISSION

The Gamma-Ray Large Area Space Telescope is an orbital observatory being planned as a joint DOE/NASA project to be launched in 2006. The objective of the mission is to view the gamma ray sky in the ranges between 20 MeV and 50 GeV using an instrument based on pair conversion and silicon detector technology. Due to the nature of the detectors GLAST will have a hemispherical view of the sky with a 0.3-2 arcminute precision, making it a very flexible instrument. It will be able to conduct allsky mapping and cataloging, be aimed at specific sources for longer time samples, and rapidly alert scientists to temporary transient behavior. Thus GLAST will be a tool for investigation of gamma backgrounds, point sources like active galactic nuclei and suspected black holes, and transient gamma-ray bursts. Increasing our knowledge of these will extend our understanding of black hole behavior, galactic formation, and cosmic origins.

### 1.2 GLAST INSTRUMENT DESIGN AND OPERATION

Gamma photons (orders of magnitude higher in frequency than X-Rays) can pass long distances through matter without interaction, and thus could not be detected with an optical telescope. Instead, GLAST detects gammas indirectly, relying on the phenomenon of charged particle pair production.

When gamma photons of sufficient energy interact with atomic nuclei, their energy can be converted into formation of an electron and positron, which can be detected with silicon strip detectors. Because momentum is


Figure-1-1 Particle pair production conserved during the conversion, tracking the paths of the charged particles allows the original path of the gamma photon to be reconstructed. If the energy of the charged particles can be measured in a
calorimeter as well, then the energy and direction of the converted photon can both be recovered. The accuracy of the tracking and calorimetry, as well as the fraction of photons which convert, will determine the performance of the instrument.


Figure 1-2 GLAST Instrument Overview

The detectors are silicon wafers with doped junctions in the form of almost two thousand parallel channels per tray. When a charged particle passes through a channel it allows a trickle of charge to flow through it, which is amplified by the tray electronics and detected. Thus locating a particle requires two detectors with perpendicular channels.

The GLAST tracker mechanism has 16 layers of converter and detector. Ideally the instrument would consist only of converter and detector layers covering an area 1.5 meters on a side, but there are several unavoidable deviations from the ideal. Because noise build up in the detector channels limits their length, the detection area must be divided into a $4 \times 4$ array of stacked detector panels, called "towers", each with its own support electronics.


Figure 1-3 Required deviations from ideal instrument design
A support structure is also necessary to hold the towers together. Although the lead converter material has a higher probability of causing a gamma photon to convert than most materials, any material in the path of the gammas can cause an undesired conversion, and any material in the path of the charged particles can perturb their paths. Thus the support structure inside the instrument must be carefully designed for low density and low conversion probability.

Finally, the spacecraft will be flying in an orbital environment filled with charged particles which must not be mistaken for converted photons. Thus an Anti-Coincidence Detector (ACD) which can detect incoming charged particles must surround the
instrument in order to discriminate ambient particles from those produced by gamma conversion inside.

Beneath each tracker tower is a cesium iodide calorimeter. Each calorimeter is made up of stacked bars of CsI, insulated from each so that the specific bars activated can be determined. Knowing the location of the bars allows the calorimeter to aid in the determination of the charged particle paths as well as net energy.

### 1.3 GRID DESIGN PROBLEM

The GLAST grid design problem comes out of the need to mount these towers and calorimeters, and the ACD. For integration and testing, the towers and calorimeters need to be removable individually, necessitating a grid structure to support them. In addition, the entire instrument must be mounted to a spacecraft that will provide propulsion, communications, attitude control, etc.


Figure 1-4 Tower and calorimeter attachment

The grid must be designed to survive launch, and perform without excessive deformation in the on-orbit thermal environment. The total grid width is one and a half meters, and it's height must be at least tall enough to accommodate the 20 centimeter tall calorimeters. The combined mass of the towers and calorimeters is over two metric tons, with the dense cesium iodide in the calorimeters contributing $75 \%$ of it. Because launch accelerations around 7 g will increase this weight to over fourteen tons, the structure must be very stiff and strong.

### 1.4 COMPOSITE MATERIALS VS ALUMINUM

The composite grid is an alternative to a grid made of aluminum, which is the baseline design that the bulk of the GLAST effort has been focused on. Naturally,


Figure 1-5 Aluminum baseline design, corner detail
this design has been evolving continuously for the past three years. Rather than attempt to continuously update the composite design in response to changes in the aluminum design, a version of the latter design frozen about a year ago will be used for comparisons for most of the text.

This design has several key features. The ribs are 6 mm thick and 20 cm tall, and have a thicker flange at the top which has through holes for attaching the towers, and embedded heat pipes for moving heat generated in the center of the grid to radiators at the edges. Protrusions on the side have a ledge for supporting the ACD, and holes on the bottom for mounting to the spacecraft bus. The overall mass is 105 kilograms.

Why we would expect composite materials to offer advantages over aluminum can be seen in the following table, which shows the relevant material properties of some representative composite laminates we might replace the aluminum with.

Table 1-1 Comparison of aluminum and cured composite prepreg properties

| Property <br> (layup) | Aluminum | T300 <br> (uni) | T300 <br> $\left( \pm 45^{\circ}\right)$ | YS90 <br> (uni) | YS90 <br> $\left( \pm 45^{\circ}\right)$ | YS90 <br> (quasi) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\rho\left(\mathrm{g} / \mathrm{cm}^{\wedge} 3\right)$ | 2.7 | 1.6 | 1.6 | 1.8 | 1.8 | 1.8 |
| Ex (GPa) | 76 | 181 | 25 | 540 | 19.6 | 180 |
| Ey (GPa) | 76 | 10 | 25 | 5.5 | 19.6 | 180 |
| Es (GPa) | 29 | 7 | 46 | 5.1 | 130 | 68 |
| Kx (W/mK) | $120-240$ | 4.6 | 2.7 | 304 | 152 | 152 |
| Ky (W/mK) | $120-240$ | 0.7 | 2.7 | 0.7 | 152 | 152 |
| CTE x $\left(\frac{\mu m}{C^{o}}\right)$ | 33 | 0.02 | 0.85 | -1.2 | -0.5 | -0.5 |
| CTE y $\left(\frac{\mu m}{C^{\circ}}\right)$ | 33 | 22.5 | 0.85 | 25 | -0.5 | -0.5 |

On the low end of carbon fiber composite materials is a standard T300/5208 prepreg. The data for a unidirectional layup and a $\pm 45^{\circ}$ layup highlight the way a laminate can be tailored for different applications. Unidirectional T300/5208 can be much stiffer than aluminum if loads are tensile or compressive and in one direction. By switching to a $\pm 45^{\circ}$ layup, however, the shear stiffness can be increased dramatically at
the expense of tensile stiffness. YS90, a very high stiffness fiber, exhibits the same tradeoffs between unidirectional and $\pm 45^{\circ}$ layups. Note that a quasiisotropic layup of YS90 is mechanically superior to aluminum in all ways. Thermally, carbon fibers have lower coefficients of thermal expansion; they expand less than aluminum when heated, with YS90 even contracting slightly. YS90 laminates, made of pitch, can have thermal conductivity comparable to aluminum, whereas T300, made of a PAN precursor, has very low conductivity. Also note that any carbon composite will have a lower density than aluminum.

The tradeoff for YS90's superior properties, of course, is price. Prepregs made of YS90 fiber are about seven times as expensive as prepgregs that use T300 fiber. However, price comparisons between a grid made of aluminum and a grid made of composite are not a simple as comparing market prices for the raw material. There is a fundamental difference between the manufacture of both grids. The composite grid is built up: material is only wasted to the extent that scraps are produced during layup. The aluminum grid is produced out of an enormous custom cast slab of metal by removal of a huge fraction of the material through hundreds of hours of machining. In the end, the combined material and labor costs for either design are not so different.

### 1.5 PROBLEM STATEMENT

The problem being addressed, then, is to provide a structural grid design that satisfies GLAST requirements using composite materials and a practical manufacturing technique. The detailed requirements the grid must meet are explained in the Design Problem section on page 22.

### 1.6 THESIS CONTRIBUTION

The contributions of this thesis work are threefold:

- A new manufacture method for making composite grids has been developed which has advantages over other methods in terms of tailorability for specific loads and ease of fabrication.
- A series of finite element models were created which are flexible enough to accommodate changes in the GLAST design or be generalized to other applications entirely.
- These models were used to make appropriate trade-offs and design a grid structure suitable for GLAST.


## CHAPTER 2: MANUFACTURE METHOD

### 2.1 INTRODUCTION

Grids made of composite materials are not a new phenomenon. Their primary use in the past has been as stiffeners for other structures, bonded to flat or cylindrical skins as reinforcement against bending moments or to provide circumferential reinforcement. They have also been used to create thermally very stable platforms.

However, grids can serve as stand-alone structures as well. Creative design can take advantage of grid geometry to accomplish structural goals that flat laminates cannot. Although the majority of structures require a continuous surface to accomplish containment, separation of environments, etc, there are some structures that must be permeable to fluids (such as gratings), require through access for wiring, lights, or inspection, or for which continuity or permeability is irrelevant In the GLAST grid the need for a grid structure was dictated by the need for inspection and through access for wiring.

A variety of methods have been used to manufacture grids out of composite in the past. Each method has different advantages and disadvantages, which will determine which should be applied to a given design problem. Our new method brings a unique combination of qualities that make it suited for the GLAST grid design as well as other applications. In this section several manufacture techniques are described to show what methods have been used in the past, and to illustrate how ours evolved out of them.

### 2.2 OTHER MANUFACTURE METHODS

### 2.2.1 SLOTTED-JOINT GRID

The simplest composite grid to manufacture is slotted-joint grid. To build this, we begin with a laminate, which we cut into the desired shape of ribs with slots which stick halfway through. These slots can be stuck together, forming the nodes of an assembled grid.


Figure 2-1 Manufacture of slotted joint grid
The advantages of this structure are the simplicity of its manufacture, and the flexibility of the layup. Properties of the grid, such as thermal expansion and stiffness, can be tailored by using different laminate layups. The disadvantage of the structure is the slots, which are weak points for failure in any kind of loading. This type of grid is usually bonded as a stiffener onto a skin on one or both sides.

### 2.2.2 INTERLACE GRID

The next technique is "interlace" grid. To manufacture it we start with a mold of the finished grid which looks much like a waffle iron. We then lay wet fibers in one direction, then in another so that they cross at the nodes of the grid. Successive layers will build up a grid made of continuous, unidirectional fiber in all the ribs, which is then cured to hardness and removed from the mold.


Figure 2-2 Manufacture of interlaced grid
The first advantage of this method is that the fibers in the rib are unidirectional, which is good when loading will be tensile or compressive forces, or bending moments in the ribs. The second advantage is that the fibers are continuous through the nodes, which makes them much stronger than adhesively bonded nodes. The disadvantages parallel the advantages. The fibers are limited to being unidirectional, which is not good for shear loads in the ribs. Because the fibers must cross at the node, the theoretical limit for fiber volume fraction in the ribs is $50 \%$, which is lower than the $70 \%$ and higher achievable with prepreg or pultruded sections.

### 2.2.3 TRIG GRID

A variation on interlace is the tooling reinforced integral grid. In this technique, the mold is not a solid female part, but is instead made of composite tube sections held in place in fixture. When the mold is interlaced and cured, the tube sections, by virtue of the bond formed with the interlace by the cured epoxy, remain a part of the grid.


Figure 2-3 Manufacture of tooling reinforced integral grid
The advantages of this method include the ability to tailor the laminate in the tube section to specific applications and still have continuous fibers through the nodes. The tube sections, which can be created through wrapping, filament winding, or pultrusion, can supplement the unidirectional interlace by, for instance, supplying resistance to shear loads. Disadvantages of this technique are the additional manufacture steps of the tube section fabrication and fixture preparation, and the limited fiber volume fraction in the interlace.

### 2.3 SLOTTED-JOINT TRIG METHOD

### 2.3.1 OVERVIEW

Our new process, slotted TRIG combines aspects of each of the three previous methods. We begin by assembling ribs out of three pieces, two "walls" and one "center" piece. Depending on the application the center could be either a low


Figure 2-4 Slotted joint TRIG rib fabrication
density foam or, as in the case of GLAST where we need all the stiffness we can get, a laminate. The key to the rib assembly is that center is not as tall as the walls, leaving an empty groove on the top and bottom edge.

From there we proceed exactly as with the slotted grid, cutting slots and assembling the grid, with one difference: we cut slots on both sides, one halfway and one as deep as the groove.


Figure 2-5 Slotted joint TRIG rib slots
The second slot means that the empty space created by the grooves is not broken up at the nodes, but is continuous over the entire grid.


Figure 2-6 Slotted joint TRIG assembly

That space now looks like the TRIG does before interlacing, providing a TRIG mold on the top and bottom which we proceed to interlace to finish the grid.

There are several advantages to this method. It shares with the TRIG method the combination of unidirectional interlace and the laminates which can be tailored to specific applications. As with the slotted joint method, the slots control the distance between the nodes, and, when the rib thickness and slot width are comparable, make it almost self-aligning, reducing necessary fixturing. Again, the continuous interlaced fibers through the nodes contribute to their strength. Additionally, the placement of the unidirectional fibers at the top and the bottom of the ribs enhances their contribution to rib bending stiffness. The disadvantage of slotted TRIG is that it has more manufacturing steps than any of the others. Each step is fairly simple and easy to control, but the tradeoff is more steps.


Figure 2-7 Summary of slotted joint TRIG manufacture

### 2.3.2 RIB MANUFACTURE

There are actually several ways to manufacture the ribs. The walls and center pieces can be layed up as separate laminates or co-cured as a single piece. In the first case we have the option of cutting the slots in the separate pieces first, then bonding them into a rib, or bonding them first, then cutting the slots. In the co-cured case we simply
cut the slots. Test ribs were created using each possible path to compare the methods for ease of manufacture.

## Three Process Paths




Figure 2-8 Three ways to manufacture slotted joint TRIG ribs
In the first scenario, the walls and center would likely be layed up as large flat panels which are cut to the sizes needed for the ribs. If the cutting is done via waterjet, it is a simple case to include the slot details at the same time. A jig can then be used to align the three pieces, which are then bonded with an adhesive film under heat and pressure.

In the second scenario, the laminates are cut or layed up to the external dimensions of the ribs, but without the details of the slots. They are bonded, then cut. Depending on the width of the empty interlace groove, waterjet cutting through the separated walls may not be possible or may require an insert. Slots can, however, be cut with a circular abrasive diamond saw.

In the third scenario, the layup process is more complex. Inserts, as shown below, must be placed where the grooves are to be located and removed after the cure.


Figure 2-9 Co-curing slotted joint TRIG rib walls and center using inserts
The inserts can be kept to keep a contained stream during waterjet cutting, as shown below, or removed if cutting is done with an abrasive diamond saw.


Figure 2-10 Cutting slots in slotted joint TRIG ribs

### 2.3.3 INTERLACE PROCEDURE

Once the ribs are made, we fit them together. Within the tolerance of the slot locations and widths, the distance between nodes is fixed. What remains is to make sure the angles are all ninety degrees, which is done by fitting it into a fixture with squared corners.

The interlace is accomplished by taking a dry fiber tow, wetting it, and winding it back and forth in the grooves that form the TRIG mold on the top of the grid. At the ends of the ribs the wet fibers are wrapped around pegs to get enough tension to keep them straight, as shown below. In our case we use nails or bolts, hammered or screwed into the wooden fixture, for the pegs. If the pegs are vertical, we've found that the tension from many layers of interlace induces enough moment to bend the peg through the wood, pulling it out and relieving the desired tension. So instead, we angle the nails so that the tension in each additional layer of interlace actually helps to compress the fibers building up around the peg.

## - Self-aligning with outer border



## - Angle nails for tension



Figure 2-11 Interlacing in a fixture using pegs for fiber tension and alignment
We use a room temperature curing epoxy to wet the fibers so that within 24 hours the first side of interlace is cured enough so that we can interlace the other side. Then we complete the cure for both in an oven. The fibers extending beyond the grid around the pegs are cut and sanded down to a smooth surface, and the teflon tape and bagging
material used to protect the grid dripping epoxy during this rather messy procedure, is removed. Interlace sticking above the tops of the grooves can be machined off to give a level surface.

### 2.4 DESIGN WITH SLOTTED JOINT TRIG

With the slotted TRIG we gain a great deal of flexibility in design, as there are many variables we have control over. Geometrically we can vary the height of the grid, the height of the center, the width of the center, and the width of the walls. We can choose the materials for the wall, the center, and the interlace. Finally, we can set the layup of the wall and, if it is a laminate, the center.


Figure 2-12 Design variables for Slotted TRIG
What happens when manipulate these variables are manipulated? Depending on the layups and materials the interactions between the variables can be fairly complex, but a simplified case can illustrate the basic principles.

Take the case of the unidirectional interlace fibers providing only tensile stiffness, and negligible shear stiffness, and a plus or minus $45^{\circ}$ layup for the center providing shear stiffness but negligible tensile stiffness. Ignoring the wall for the moment, the theoretical bending stiffness of the rib, it's resistance to moments, will be proportional to the stiffness of the interlace, the cross-sectional area of the interlace, and the square of the distance from the middle of the beam. The shear stiffness, it's resistance to opposing
vertical forces displaced along the beam length, will be proportional to the shear stiffness of the center material and the cross-sectional area of the center.

Rib Bending Stiffness $\propto E_{\text {tensile }} A_{b} z^{2}$


Rib Shear Stiffness
$\propto E_{\text {shear }} A_{s}$


Figure 2-13 Factors affecting theoretical bending and shear stiffness in ribs
If we change the depth of the interlace, as shown to the right, we change the proportions of the beam materials contributing to bending and shear stiffness. Including the wall again, we note that the different wall layups can contribute more towards one or the other types of stiffness as well. Thus by altering the geometry and layups, the proportions of the cross-section contributing towards resisting different loads can be tailored to match the needs of different applications. If higher stiffness is required, more expensive, higher stiffness fibers can be used where necessary.


Figure 2-14 Tailoring ribs for shear or bending resistance

### 2.5 CONCLUSION

Many methods exist for manufacturing composite grid structures. For the case of GLAST, however, where the boundary conditions make shear stiffness as much a concern as bending stiffness and the nodes must be very strong, the slotted TRIG is the only viable design. Slotted joint grid, even with reinforcement, is not strong enough, interlaced grid does not provide enough shear stiffness, and TRIG is too hard to control for the necessary GLAST tolerances. Although the instrument operation and interfaces place constraints on the external dimensions of the grid cross-section, slotted joint TRIG can be tailored to maximize the usefulness of the material that can be placed in this limited area.

## CHAPTER 3: DESIGN PROBLEM

### 3.1 INTRODUCTION

This section describes the design problem of the grid on several levels. First, the actual requirements used in the grid design are presented. Then the methods used to satisfy or solve each of the requirements are shown.

### 3.2 DESIGN REQUIREMENTS

The GLAST grid design is integrally tied to the overall vehicle design, in which the grid serves a mechanical, structural, and thermal role. Mechanically it must interface to the calorimeters, towers, anti-coincidence shield, and the spacecraft. Structurally it is the primary load-bearing member in the instrument. Thermally, it must accommodate heat flow from the towers without heating the calorimeters or distorting significantly under temperature gradients.

The requirements on the grid can broadly be divided into two categories: those that are imposed by the required interfaces, and those imposed by the on-orbit and launch environments. These will be explained in detail in the following two sections, and summarized in the overview.

### 3.2.1 INTERFACES AND INSTRUMENT ACCOMODATION

As the principle load-bearing structure in the instrument, the grid must accommodate the geometry of the other instrument components and connect to them in a manner secure enough to carry the resulting loads. The four major interfaces, as discussed in the instrument description, are to the calorimeters, tracker towers, spacecraft bus, and the anti-coincidence detector (ACD).


Figure 3-1 Grid interfaces to towers, calorimeters, ACD, and spacecraft
The telescope precision relies on very tight clearances between instrument components, so all grid walls should be located within a plus or minus 20 mil tolerance.

### 3.2.2 LAUNCH AND ORBITAL ENVIRONMENT

GLAST will be launched on a Delta II rocket. To qualify for acceptance the grid structure must not fail under 7.25 g static loading. In addition to static loading, the Delta II puts out random excitation, with most of the energy of the excitation in the frequency range below 50 Hz . To avoid channeling this energy into violent resonance of the structure, the first frequency of free vibration should be above 50 Hz .

The orbital environment puts thermal demands on the grid as well. Without convection, heat generated by the electronics in the calorimeters must be removed by either conduction or radiation. Radiators on the non sun-facing sides of the grid will radiate the heat to space once it has been moved there, but it must be conducted there either by the grid web or by the heat pipes embedded in the top of the grid.

With thermal conduction comes a thermal gradient and consequent deformation of the grid, which will perturb the location of the sensors in the towers. Because the materials are orthotropic, uniform changes in temperature will cause only expansion or contraction of the grid dimensions. Only a gradient through the thickness of the grid will
create a significant curvature of the grid surface. A steady state deformation can be taken into account through on-orbit calibration of the sensors. However, in the planned 600 km altitude, $29^{\circ}$ inclination circular orbit, the eclipse time, when the sun is blocked by the earth and not contributing heat, will vary between 27 and 35 minutes each 97 minute long orbit. Although active control such as cycling heaters and moving radiators may be used to minimize changes in the thermal gradient, the continuous thermal cycling will cause variations in temperature which will result in continuous movement of the sensors throughout the course of the mission. To the extent that the coefficient of thermal expansion of the grid materials is linear over the temperature range experienced in orbit, it is not the change in absolute temperature, but rather the change in the temperature gradient that determines how the grid bends.

At this time the thermal control system is not known and thus the expected change in the gradient, which would require a transient analysis and knowledge of the spacecraft attitude throughout an orbit, cannot be predicted. However, we do know that the instrument will be assembled at room temperature but be operated with the radiators at around $0^{\circ} \mathrm{C}$, and the resulting gradient and deformation can be modeled. The cyclic changes will be perturbations around this steady state gradient. Comparing the steady state model results for different designs provides a way to at least determine their relative sensitivity to thermal gradient changes.

Qualitatively, the mass of the grid should be minimized. Given the expense of flying in space, we would like to maximize the amount of mass that can be allocated towards scientific hardware rather than to structural support.

## OVERVIEW OF REQUIREMENTS

The requirements can be summarized as:

## Structural

Interface to towers, calorimeters, $\mathrm{ACD}, \mathrm{S} / \mathrm{C}$ bus
$\pm 20$ mil dimensional tolerance

## Launch

Sustain 7.25 g
First free vibration mode above 50 Hz

## Thermal

Minimize thermal deformation
Qualitative
Minimize mass

### 3.3 DESIGN SOLUTION

Each of the requirements listed above can be satisfied. In some cases, as with the interface between the towers and grid, the requirement is met by proposing a mechanical design. In others, as with the first free vibration mode, it is met with a methodology that, when followed, will lead to a valid design. Following is a list of how the various requirements can be met.

### 3.3.1 TOWER INTERFACE

As in the baselined aluminum design, the towers will be mounted atop a thicker aluminum flange on top of the thinner, 6 mm thick grid web. The flange cross-section is generally 2.5 cm wide and 1.5 cm tall, but the width varies in places to allow clearance space for cables going to the tower electronics. Through holes allow for installation of bolts that keeps the towers in place. Heat pipes embedded in the aluminum flange move heat generated in the middle of the grid to radiators on the perimeter.


Figure 3-2 Tower interface using aluminum flange
The aluminum flange has a groove in the bottom surface which acts as a female fitting for the top of the 6 mm wide composite grid web.

A major design concern is the thermal expansion mismatch between the aluminum flange material and the composite grid material. Because the instrument will be assembled at room temperature but have the heat pipes operate at $0^{\circ} \mathrm{C}$, the different thermal expansions of the materials will cause stresses in both the flange and grid as well as shear stress in the bond. A simplified analytical model of a single rib, in which only the extension or compression of the two materials is considered (and not their bending), can be used to estimate these stresses as a function of the change in temperature. Assuming a composite rib which is unidirectional YS90A/25C prepreg, a 6 mm deep groove in the flange which is 2024-T6 aluminum, and a bonding epoxy such as HYSOL EA 9628, this model suggests that within the expected 0 to $35^{\circ} \mathrm{C}$ temperature range thermal expansion mismatch between the aluminum grid and composite web will not be sufficient to cause dangerous stresses, which only approach yield with around a $\pm 100{ }^{\circ} \mathrm{C}$ change. The finite element model of the grid, described in section 4.3 , corroborates this.

Naturally, real world processing will lead to irregularities in the bond, which will need to be tested. Theoretically, however, the bond should be safe.

### 3.3.2 CALORIMETER INTERFACE

The calorimeter is inserted into the grid cells from below. Once it is in place, L bracket "shelves" are installed underneath at the corners. The brackets bolt to the calorimeters, and through holes in the grid and brackets allow them to be bolted together with the brackets in adjacent cells. If necessary, a thin fiberglass scrim cloth could be included in the layup over the locations that will be drilled to prevent fraying of the unidirectional prepreg layer.

Grid Cell



Figure 3-3 Calorimeter interface using mounting brackets
For this design, the calorimeter connection determines how tall the grid ribs must be. We do not want the through holes to pass through the interlace, causing stress concentrations in the most stressed part of the structure. Preliminary modeling determined that 3 centimeters of interlace would be just sufficient to meet the design criteria, and that more would unnecessarily increase the overall grid height. Thus the ribs are 24 centimeters tall with 3 centimeters of interlace depth on the top and bottom, leaving room for the 20 centimeter tall calorimeter to be supported by the L brackets.

### 3.3.3 SPACECRAFT AND ACD INTERFACE

During the Delta II launch GLAST will ride on top of the spacecraft bus inside a 3 meter fairing. The bus will be mounted to a payload attach fitting, which is an integral part of the launch vehicle. Thus loads must flow from the instrument and grid into some sort of adapter, to the spacecraft bus, and finally into the payload attach fitting.

Because the instrument and spacecraft bus are contracted separately, the adapter and spacecraft have yet to be designed. Thus the first step in attaching to the adapter is to make a good assumption about what the adapter will be. The strategy will be to find a set of boundary conditions which favor higher natural frequencies but are mechanically reasonable. This problem is examined in more detail in the discussion of the finite element model in section 4.2 .


Figure 3-4 Launch vehicle configuration and grid support pattern
The results of that investigation yield the 8 point pattern shown above on the right. The interface at the nodes will be exactly the same as the aluminum baseline shown before, aluminum bosses that stick off of the grid and provide support ledges for the ACD as well as a mounting surface for the spacecraft adapter.


Figure 3-5 Schematic of spacecraft adapter mounting bosses
How are the bosses, machined out of aluminum, attached to the composite grid? In principle, the load transfer between the grid and bosses bonded to its side should be through shear. By symmetry the load on each bond should be one eighth of the total load, 1.6E5 N, spread over the bonding area of $6 \times 6 \mathrm{~cm}$ : a shear stress of 5.6 MPa. If the joint experienced only shear, a structural epoxy such as HYSOL EA 9628, with a lap shear strength of 38 MPa , would be more than sufficient.

However, some of the loading (which includes not only launch, but months of testing and integration) will not be shear, and the peel-off strength of a flat epoxy bond is very low. We must communicate the load into the grid, not just to its surface. This can be accomplished by modifying the manufacture of the ribs described in section 2.3.2 . As shown below, the ribs with bosses on their ends are laid up differently, with removable inserts which reserve a space for tongues included on the machined bosses to be inserted later.


Assembled ribs accommodate plug-in bosses


Figure 3-6 ACD and spacecraft adapter interface uses insertable aluminum bosses
Lab specimens of smaller scale ribs joints, in which aluminum inserts were bonded, were tested and demonstrated failure strengths for pull-out of the aluminum in good agreement with theoretical predictions based on the epoxy strength.

To be able to insert all the bosses on the bottom of the grid, the slots of the outside ribs must all be on the bottom. This complicates the design of the ribs, as they can no longer be interchangeable. Two keep all outside rib slots on the bottom we must use two different patterns of slots on the ribs and assemble them as shown below.


Figure 3-7 Rib assembly as modified for aluminum boss design

### 3.3.4 DIMENSIONAL TOLERANCE

Achieving a $\pm 20$ mil tolerance is an unusual requirement for a composite grid structure, which is usually designed for external panel dimensions and global behavior. It is difficult to achieve such tolerance with the general non-uniformity of the materials and their processing. Three factors are most important in determining dimensional tolerance for slotted TRIG, flatness of the panels used in the ribs, accuracy of the cutting of the slots, and clearance designed into the slots.

Unbalanced layups, uneven resin bleeding, and uneven heating and curing can all compromise the flatness of composite laminates. Curvature along the lengthwise direction of the grid is not so important, as the intersections of the ribs at the nodes will
tend to straighten them when put into a square fixture. Curvature or warping in the transverse direction, however, can misalign the top and bottom of the edges of the grid where the interlace is supposed to go, and interlacing such a misaligned grid will make the misalignment permanent. Professional manufacturers of laminates, however, claim that flatness can be controlled to $\pm 12$ mil over the area of a $150 \mathrm{~cm} \times 125 \mathrm{~cm}$ panel (a size that could be cut to yield 4 ribs).

Although some clearance beyond the 6 mm width of the ribs must be designed into the slots, too much will provide too much play at the intersection and consume more than the necessary share of available tolerance. To isolate the clearance issue, we can make rib intersections using aluminum ribs (which will be cheap and flat) with carefully machined slots of different widths, empirically determining the minimum clearance to allow an easy fit.

Because waterjet cutting is the only way to get precise, narrow cuts in ribs 20 cm tall and 150 cm long without building expensive jigging, the limit on accuracy of slot dimensions and locations is set by the limit on waterjet accuracy. Professional waterjet companies claim that accuracies of $\pm 5 \mathrm{mil}$ are achievable. To test the accuracy of assembling a slotted grid from waterjet cut ribs a cheaper aluminum grid can be assembled and measured for tolerance.

Theoretically, the sum of the errors from these three sources should be within $\pm 20$ mil. Because funding for the project was cut before the described tests could be completed, though, satisfaction of this requirement has not been verified empirically.

### 3.3.5 LOAD, FREQUENCY, AND THERMAL REQUIREMENTS

Resisting failure under 7.25 g static loading, achieving a first free vibration frequency above 50 Hz , and preventing excessive thermal deformation are all design goals very dependent on the materials and layups used for the composite web. With the dimensions of the grid determined from the accommodation requirements and designed interfaces for the tower, calorimeter, ACD, and spacecraft bus, the variables that remain to be determined are wall thickness, wall, center, and interlace material, and wall and center layup.

With eight discrete support points and ten non-slender beams with complex, multi-material cross-sections, analytical modeling of the GLAST grid is not a viable option. Instead, finite element models are used to predict grid performance and evaluate how well given choices of variables may work. Using the ANSYS programming language the search through these hundreds of variable combinations can be automated. A detailed description of the models used for each criterion and their results is included in the following section.

## CHAPTER 4: FINITE ELEMENT MODELING

### 4.1 MODELING OVERVIEW

### 4.1.1 TOOLS AND ELEMENTS

Finite element modeling for the GLAST grid structure was done using ANSYS 5.6, a commercially available modeling program licensed to SLAC and Stanford. Finite element modeling is a powerful tool for engineers, allowing the simplification of loads on complex geometries into computational problems tractable by modern computers. Of course, as with all modeling techniques, it can be misapplied. Model results should be compared to analytical predictions whenever possible, the density of the element mesh should be sufficient to demonstrate convergence of results, and exact values of stress in regions of high rates of change in stress should be checked carefully.


SHELL 99 (quadratic laminate element) - used for ribs and tray
BEAM 189 (quadratic beam element) - used for flange
Figure 4-1 Finite element model of GLAST grid structure

Several types of elements available in ANSYS were used to model the grid structure. For the natural frequency and load modeling, SHELL 99 was used. SHELL 99 is an 8 node quadratic quadrilateral capable of modeling laminates with linear behavior and six degrees of freedom at each node. The element is ideal for composite modeling because the user can specify any layup of orthotropic materials up to 250 layers. This element was used for the grid web and to model the sandwich panels at the bottom of each tower.

To model the aluminum connection grid, BEAM 189 elements were used. They are quadratic, which allows the nodes to line up with the quadratic SHELL 99 elements in the grid web. To model the calorimeter and tower masses, MASS 21 elements were used. The mass elements were located at the points on the grid where the objects they are modeling would be connected to it. Thus the tower masses are distributed over the top flange and the calorimeter masses are in the bottom corners of the grid cells just above the interlace.

Because SHELL 99 elements do not model thermal conductivity, a separate thermal model constructed of SHELL 57 elements, which accommodate thermal conductivity but do not model thermal expansion, had to be created. Temperature results from the thermal model could be substituted back into the structural model to determine thermal distortion.


Figure 4-2 Two modeling steps to find thermal expansion

### 4.1.2 ANALYTICAL VALIDATION

To gauge the confidence we should have in the results of finite element models of the complex GLAST grid structure, we should use the same elements to construct simpler models that we can compare to analytical predictions. Three cases are necessary to demonstrate that the elements as used correctly model stiffness, ply failure, and thermal conductivity and expansion as we'd expect them to.

## STIFFNESS

To validate stiffness of the elements used in the structural model we will isolate a single grid rib and give it the boundary conditions of a cantilever. The rib is $1.5 \mathrm{~m} \times 0.3$ m and is 6 mm thick, and can be modeled analytically as a cantilever beam. The classic governing equations for deformation from bending and shear, $d_{\text {bending }}=\frac{P L^{3}}{3 \sum E I}$ and $d_{\text {shear }}=\frac{P L}{\sum A G}$, are used for the analytical model.


Figure 4-3 FEM stiffness verification model
Three cases for modeling materials will be examined, isotropic aluminum, orthotropic T300/5208 prepreg with all fibers aligned in the lengthwise $\left(0^{\circ}\right)$ direction, and a T300/5208 layup with T300 interlace design. The last design uses 1 mm thick walls that are balanced $\pm 15^{\circ}$, a 4 mm thick balanced quasiisotropic core, and an interlace made of $40 \%$ volume fraction T300 fiber to a depth of 3 cm . Two loading conditions, 1000 N of in-plane loading and 10 N of out-of-plane loading, are considered, both with the other end fixed as a built in support.

The results and errors are shown below

Table 4-1 Comparison of FEM and analytical stiffness results

| In-Plane Deflections (mm) |  |  |  |
| :--- | :--- | ---: | ---: |
|  |  |  |  |
|  | FEM Analytical \% error |  |  |
| Aluminum | 1.14 | 1.15 | 0.87 |
| T300/5208 0's | 0.62 | 0.60 | 2.85 |
| T300/5208 design | 0.85 | 0.84 | 1.80 |


| Out-Of-Plane Deflections (cm) |  |  |  |
| :--- | ---: | ---: | ---: |
| FEM Analytical \% error |  |  |  |
| Aluminum | 2.69 | 2.74 | 1.82 |
| T300 0's | 1.16 | 1.16 | 0.34 |
| T300/5208 design | 1.49 | 1.46 | 2.05 |

While the error on the in-plane deflection of the $\mathrm{T} 300 / 52080^{\circ}$ model is almost $3 \%$, it is really due to the fact that the analytical prediction does not take into account transverse compression in the beam, effectively assuming the transverse stiffness is infinite. When the analytical assumptions are matched by making the transverse stiffness of the FEM four orders of magnitude higher (effectively infinite), the error is reduced to 0.32 \%.

## FAILURE

To validate the failure prediction capabilities of the model, the same plate from the previous example will be used. In this case we will apply a pure tensile load to the plate by pulling it in the x direction with a total of 1000 N force. For the SHELL 99 laminate elements ANSYS can calculate the maximum of the inverse of the Tsai-Wu strength ratio among all the plies, thus pointing out the weakest ply under those load conditions and how close to failure it is.

The first plate, made of 24 unidirectional plies of T300/5208 oriented in the x direction, is simple to analyze. The average stress will be

$$
\sigma_{x}=\frac{\text { Force }}{\text { height } \cdot \text { thickness }}=\frac{1000 \mathrm{~N}}{0.3 \mathrm{~m} \cdot .006 \mathrm{~m}}=5.556 E 6 \frac{\mathrm{~N}}{\mathrm{~m}^{2}}
$$

Given the failure properties of T300/5208 plies

Table 4-2 Failure properties of cured T300/5208 prepreg

| Failure of T300/5208 in MPa |  |  |
| :--- | ---: | ---: |
| tensile |  |  |
| $X$ | 1500 | 1500 |
| $Y$ | 40 | 286 |
| Shear | 68 |  |

The $1 / \mathrm{R}$ value can be calculated as $3.70 \mathrm{E}-4$. In this case of only normal stress in the x direction this can be simply confirmed by dividing the stress in the x direction by the failure stress in that direction to get the same result. In the FEM a slice taken from the middle of the plate reveals a variation between 3.70E-4 and 3.72E-4.

The second plate has a more complex layup, and thus a more complex analytical solution. The stresses in the individual plies are not known until extension of the plate is solved for. To arrive at the maximum ply failure ratio we must first determine the overall laminate stiffness. The stiffness and loading are used to calculate strain, which will be identical for each ply. The strain can converted into stress on a ply-by-ply basis, or the failure strength criteria can be converted to failure strain criteria, both using individual ply stiffnesses. Either way, the resulting strength ratios can be calculated and the ply closest to failure can be determined. For analytic simplicity the core was assumed to extend to the top and bottom of the walls and the interlace was not included in this comparison.

Following this procedure yields the stresses in each ply and the following inverse strength ratios.

Table 4-3 Comparison of FEM and analytical failure results

| Inverse Strength Ratio $1 / R * 10 \wedge 3$ <br> ply angle <br> plor |  |  |  |
| ---: | ---: | ---: | ---: |
| 15 | 0.743 | 0.742 | 0.081 |
| -15 | 0.743 | 0.742 | 0.081 |
| 0 | 0.666 | 0.665 | 0.090 |
| 45 | 1.138 | 1.141 | 0.290 |
| -45 | 1.138 | 1.141 | 0.290 |
| 90 | 1.428 | 1.434 | 0.399 |

## THERMAL CONDUCTIVITY

To validate thermal conductivity of the SHELL 67 elements we will model a simple plate one meter long, 10 cm tall, and 6 mm thick. The boundary conditions will include insulation on the top and bottom sides. The left side will be supplied one watt of power and the right side will be set to $0^{\circ} \mathrm{C}$. For thermally orthotropic materials, the material will be rotated $90^{\circ}$ in order examine conduction in both the x and y axes of the material.


Figure 4-4 FEM thermal conductivity verification model

Three test materials are considered: isotropic aluminum, cured T300/5208 prepreg unidirectional in the x direction, and a laminate made of T300/5208 with the same layup as described in the stiffness validation above. The thermal properties appear as follows. Alpha is the coefficient of thermal expansion and K is the thermal conductivity.

Table 4-4 Thermal properties of aluminum and T300/5208 layups

|  | alpha $x$ <br> $(\mu \mathrm{~m} / \mathrm{m})$ | alpha $x$ <br> $(\mu \mathrm{~m} / \mathrm{m})$ | Kxx <br> $(\mathrm{W} / \mathrm{mK})$ | Kyy <br> $(\mathrm{W} / \mathrm{mK})$ |
| :--- | ---: | :--- | ---: | ---: |
| Aluminum | $2.30 \mathrm{E}-05$ | $2.30 \mathrm{E}-05$ | 240 | 240 |
| T300/5208 uni | $2.00 \mathrm{E}-08$ | $2.25 \mathrm{E}-05$ | 4.62 | 0.72 |
| T300/5208 layup | $3.19 \mathrm{E}-06$ | $1.83 \mathrm{E}-05$ | 4.00 | 1.34 |

To calculate the conductivity of the laminate from the ply properties and orientations is straightforward. When calculating off-axis properties the conductivities can be operated on like stiffnesses, and when combining to get total laminate properties
the off-axis conductivities can be averaged. Calculation of off-axis thermal expansion is also the same as stiffness, but the off-axis values cannot be simply averaged because the stiffness of each layer affects deformation as well. A stiffness weighted sum of all N plies is used instead.

$$
\alpha_{x, l a m}=\frac{\sum_{1}^{N} \alpha_{x, i} Q_{x x, i}}{\sum_{1}^{N} Q_{x, i}}
$$

The analytic prediction for heat difference across the plate uses the rule of conduction which can be written as $\Delta T=\frac{P d}{A K}$, where $\Delta \mathrm{T}$ is the difference in temperature between two sides of the plate, P is the total power passing through the plate, d is the distance between two sides, A is the cross-sectional area that the heat travels through, and K is the thermal conductivity constant for the material in $\mathrm{W} / \mathrm{mK}$.

Following is a comparison of the analytic and modeled results.

## Table 4-5 Comparison of FEM and analytical thermal expansion results

|  | $\Delta \mathrm{T}$ at $0^{\circ}$ <br> analytic$\quad$ FEM | $\Delta \mathrm{T}$ at $90^{\circ}$ <br> analytic |  | FEM |
| :--- | ---: | ---: | :--- | ---: |

## THERMAL EXPANSION

To validate the thermal expansion model we can use the same plate used to validate conductivity, incorporating thermal expansion, and compare the results to analytic predictions. In ANSYS we can replace the thermal modeling SHELL 67 elements with SHELL 63 elements (both have four nodes). To restrict the problem to one dimension, we will fix the top and bottom of the plate in $y$ to prevent expansion


Figure 4-5 FEM thermal expansion verification model

The expected expansion in the x direction is easy to calculate. Given the definition of the coefficient of thermal expansion, $\alpha$, we have a relation between strain and temperature change

$$
\varepsilon=\alpha\left(T_{\text {final }}-T_{\text {init }}\right)
$$

Because thermal expansion is prevented in the $y$ direction, there will be stress in that direction which will result in an additional strain in the x direction proportional to Poisson's ratio and the ratio of Ey to Ex. Since the temperature difference will be linear and initial temperature is zero, we can integrate along the length to get

$$
\begin{aligned}
& \Delta x=\int_{0}^{L}\left(\varepsilon_{x}+\varepsilon_{y} \frac{E_{y}}{E_{x}} v_{x y}\right) d x=\int_{0}^{L}\left(\alpha_{x}+\alpha_{y} \frac{E_{y}}{E_{x}} v_{x y}\right) T(x) d x \\
& =\left(\alpha_{x}+\alpha_{y} \frac{E_{y}}{E_{x}} v_{x y}\right) \int_{0}^{L} \Delta T \frac{x}{L} d x=\left(\alpha_{x}+\alpha_{y} \frac{E_{y}}{E_{x}} v_{x y}\right) \frac{\Delta T}{2} L
\end{aligned}
$$

Where $\Delta \mathrm{T}$ is as previously calculated during the thermal conductivity verification.

The predicted $\Delta \mathrm{x}$ and modeled $\Delta \mathrm{x}$ were identical to several significant digits, as shown below.

> Thermal expansion (m)

|  | analytic | FEM |
| :--- | :--- | ---: |
| Aluminum | $1.47 \mathrm{E}-07$ | $1.49 \mathrm{E}-07$ |
| T300/5208 uni | $6.83 \mathrm{E}-05$ | $6.83 \mathrm{E}-05$ |
| T300/5208 layup | $1.30 \mathrm{E}-03$ | $1.30 \mathrm{E}-03$ |

### 4.2 FREQUENCY MODEL

### 4.2.1 MODEL FEATURES

The frequency model was used to investigate first natural frequency of the grid structure in order to predict designs that will meet the minimum frequency requirements. The model allows a variety of materials and layups to be examined and compared. Because the GLAST design continues to change, nothing in the model is hardwired. The model is built and run using the ANSYS scripting language. Since all dimensions, masses, material constants, restraints, etc. are defined at the beginning of the script, every aspect can be easily identified and changed. A listing of the script and the variables that can be changed is included in Appendix A.

### 4.2.2 MODELING TECHNIQUE

The various components of the grid/instrument system that must be modeled include: the grid itself, the aluminum connection grid, the towers, and the calorimeters. Each of these is modeled to varying degrees of exactness, depending on their relevance to the problem of finding first natural frequency.

## COMPOSITE GRID

The walls of the grid are made up of several different materials, and are modeled by separating the individual panels into subsections with similar materials. Figure 4-6 depicts a rib removed from an already interlaced grid, and a single "panel" of the rib divided into sections according to the materials used there. Clearly, there will be a top and bottom section with the interlace sandwiched between walls, and a middle section with the core sandwich between walls. The tabs on the four corners are interlace only, because the walls have been cut here to allow the ribs to intersect. Note that the panel
includes the slot cut for perpendicular ribs. The only attachment between intersecting ribs, where they will share nodes in the model, is at the interlace.


Rib panel after interlace


Section of interlaced rib showing material regions
Figure 4-6 Diagram of different regions used in finite element modeling of the rib

## ALUMINUM GRID

The aluminum grid on top of the composite grid serves as a connection point for the towers and to hold the heat pipes that transport heat generated by the towers and calorimeters to external radiators located on the perimeter of the grid. It is bonded to the composite grid, stiffening the system, and can be modeled with beam elements having the appropriate rectangular cross-section.

## TOWERS

The effect of the towers on the overall natural frequency of the system is twofold. They add mass, and the bottom tray of the tower, bolted to the aluminum grid, adds stiffness. Modeling the towers on a tray-by-tray basis would vastly increase the number of degrees of freedom and add complication to the model, but it can be avoided.

Fortunately, the towers are very stiff compared to the grid stiffness. Structural testing and modeling by a contractor indicates the tower stiffness will be around 500 Hz , an order of magnitude higher than expected for the grid. Although the mass of the towers is distributed evenly over their height, this should have little effect on the first frequency we are interested in. The mode shape of the lowest frequency should be a "drumming", with the center of the grid oscillating up and down. For this mode, as long as the mass is located at the top of the grid, it should make little difference how high up it is. Thus the towers can be modeled as sandwich elements representing the bottom trays and as mass elements, all attached to the aluminum connection grid.


Figure 4-7 Vertical versus horizontal motion of masses in first mode

## CALORIMETERS

The calorimeters, like the towers, are simplified as well. Because the final design of the calorimeters, and therefore their stiffness, is not known, a conservative approach would be to assume they contribute no stiffening to the structure at all. Instead, their masses will be accounted for by distributing them to the four lower corners of each grid cell, where the calorimeters would be connected. In reality the mass of a calorimeter will not be distributed evenly between its four connection points, but again, for the modes we are concerned with, there should be little difference.

### 4.2.3 CONVERGENCE OF THE MODEL

Before the model can be used to predict behavior of an actual instrument, we must be sure that the element mesh density is sufficient. In the limit as the number of elements becomes infinite, the model should become more and more accurate. For economy of computing time, will want to know what is the minimum number of elements we can use to get a reasonably accurate solution.

There are three different variables that affect mesh density, number of elements across the width of the panel, number up the height of the non-interlaced section, and the number up the height of the interlace. The width of the slot at the edge of a panel, because it is so narrow, is just one element. These values propagate through the aluminum grid and tower tray components of the model because they are attached to the top of the composite grid and their nodes must thus line up with the composite grid nodes.


Figure 4-8 Parameters for determining FEM mesh density of ribs

For the simple case of an aluminum grid, we can examine the effects of varying these parameters. Shown below are a series of tables showing variation of frequency found for number of elements up the non-interlaced area ( N ) versus number of elements up the interlaced area (I), each table representing a different number of elements across the width (W). The software used, an ANSYS university license, allows a maximum of 32,000 elements. Thus the tables are blank for models using more than 32,000 elements. Note that frequency values are included to the second decimal place only to illustrate convergence of the numbers, not because they have any physical significance

Table 4-6 First natural frequency as a function of mesh density

| $W=1$ | N |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| I | 2 | 4 | 6 | 8 |
|  | 49.55 | 49.07 | 47.47 | 47.17 |
|  | 49.40 | 48.94 | 47.33 | 47.03 |
|  | 49.33 | 48.88 | 47.28 | 46.98 |
|  | 49.29 | 48.85 | 47.24 | 46.94 |


| $\mathrm{W}=2$ | N |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| I | 2 | 4 | 6 | 8 |
| 1 | 49.44 | 48.96 | 48.71 | 48.60 |
| 2 | 49.36 | 48.90 | 48.65 | 48.53 |
| 3 | 49.31 | 48.86 | 48.61 | 48.49 |
| 4 | 49.02 |  |  |  |


| $W=3$ | N |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| I | 2 | 4 | 6 | 8 |
|  | 49.14 | 48.87 | 48.74 | 48.67 |
|  | 49.10 | 48.84 | 48.71 |  |
|  | 49.05 | 48.81 |  |  |
|  |  |  |  |  |


| W = 4 | N |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 2 | 4 | 6 | 8 |
|  | 48.98 | 48.80 | 48.71 |  |
|  | 48.96 | 48.79 |  |  |
|  | 48.93 |  |  |  |
|  |  |  |  |  |

In the above tables we can clearly see the convergence of the calculated frequency, with a weaker dependence on I than W or N . A much longer running but
more finely meshed model, with $(\mathrm{W}, \mathrm{N}, \mathrm{I})=(6,10,4)$, yields 48.5 Hz . Since the primary purpose of this model is to compare different materials and layups, and the disparity between reality and the idealized model will certainly be more than 1 Hz , using $(\mathrm{W}, \mathrm{N}, \mathrm{I})=$ $(4,4,2)$ should be sufficient. Unless otherwise stated, this will be the mesh density used in the following analyses

### 4.2.4 BOUNDARY CONDITIONS

The problem of determining boundary conditions for the grid comes in two parts. First, determining which parts of the grid will be supported by the spacecraft bus or the adapter to the spacecraft bus and second, determining what the stiffness of those connections will be. Each will be dealt with below.

## SPACECRAFT BUS ADAPTER CONNECTIONS

Because GLAST cannot have any mass in between it and its hemispherical field of view, the spacecraft bus, which includes the attitude determination and control, propulsion, communication subsystems, etc., must be located below the instrument. The spacecraft bus (rather than the delicate instrument) will be attached to the launch vehicle via a circular payload attachment fitting, which is shown superimposed on the grid below. Therefore all launch loads communicated to the instrument must pass from the PAF through the bus and into the instrument support grid. Assuming we should connect at the nodes of the grid, out of the many ways this could be done, which one will minimize the first natural frequency?


Figure 4-9 Delta II payload attach fitting with grid dimensions superimposed
Shown below is an array of different candidate support footprints. Because we do not know how stiff the connections will be, two limiting cases are considered. In the first, the connection points only restrain the model in the vertical $z$ direction. Although this leaves three rigid body modes (translation in x and y , and rotation about the z axis), they can be ignored and the fourth mode considered. In the second, the connection points restrain the model in all directions. In neither case were the nodes constrained in rotation in any direction. The results of these two conditions for an all aluminum grid are shown.


Figure 4-10 First natural frequency for various candidate spacecraft adapters for two cases of constraint at mounting points

An additional constraint is that the region under the grid must be accessible by hand after the instrument has been integrated with the spacecraft bus. Wires connecting the computing elements at the base of each calorimeter must be connected and disconnected. Because we want to minimize the mass of the support structure, the most direct load bearing route between the grid and the PAF is also desirable. Given the above results and constraints, the "octagonal" layout using 8 points was chosen.

Thus an octagonal layout of supported nodes will be used to support the grid. Given the masses and loads involved, and the tight tolerances necessary to prevent rotation of the joints, we will assume that they are free to rotate in all axes (although the option to model a torsional stiffness here is included in the script).

### 4.2.5 RESULTS

A thorough examination of layup possibilities for three examples of material combinations is presented here. The first combination is T300/5208 prepreg for the walls and core and T300 fiber for the interlace ( $40 \%$ fiber volume in each case). The second combination is a hybrid with T300/5208 prepreg and high stiffness YS-90A fiber as the interlace. The final combination is YS-90A prepreg and YS-90A fiber. For each material combination the wall and core layups are varied independently, varying as
balanced angle laminates, $0^{\circ} / 90^{\circ}$ laminates, or quasiistropic laminates when possible. Further, the width of the walls are varied between 4 plies and 8 plies. Since the total width of the ribs is 24 plies ( 6 mm ), the core is supplemented with additional $0^{\circ}$ plies in the center when necessary to produce a balanced laminate.

The boundary conditions used are the worst case in which the eight support points prevent only out-of-plane motion. The resulting three rigid body modes are ignored, leaving the first three modes with shapes as shown below.


The only mode of interest here is the drumming mode, however. The second mode, in which the grid extends along the diagonal, is an artifact of the model. Although distributing the mass elements representing each tower around the top of the cell the tower is mounted on is a reasonable assumption for modeling vertical motion, in the case of in-plane motion it allows the masses to move independently of each other, inconsistent with the actual mass distribution in the tower. Similarly, the calorimeter masses are each divided into four discrete elements without regard to the calorimeter stiffness (which is unknown because the calorimeter design in not complete), which would reinforce against in-plane deformations of the cells. To a lesser degree this same argument applies to the third mode as well. Note that after the instrument is mounted on the support structure that connects it to the rocket, modes in which the grid as a whole moves in-plane must still be considered, but will depend on the stiffness of that support structure.

Listed below are the results of this examination for the first mode. In each case the highest natural frequency design is highlighted.

T300/5208 walls / T300 interlace

Drumming Mode -4 ply thick walls

|  | walls |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| core | 0 | 15 | 30 | 45 | 60 | 75 | $900 / 90$ |


| 0 | 41.5 | 45.0 | 47.9 | 48.4 | 47.3 | 44.1 | 40.8 | 42.4 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 15 | 45.6 | 47.6 | 48.6 | 48.4 | 47.7 | 45.8 | 43.7 | 46. |
| 30 | 48.3 | 49.1 | 47.3 | 45.4 | 45.4 | 44.8 | 43.7 | 7.4 |
| 45 | 48.7 | 48.9 | 45.6 | 41.4 | 40.6 | 40.6 | 40.1 | 45.7 |
| 60 | 48.0 | 48.4 | 45.3 | 40.4 | 37.9 | 37.3 | 36.8 | 44. |
| 75 | 45.7 | 46.7 | 44.7 | 40.3 | 37.3 | 35.8 | 34.9 | 42.0 |
| 90 | 42.2 | 44.6 | 43.9 | 40.1 | 36.9 | 34.9 | 34.9 | 39. |
| 0/90 | 43.3 | 46.5 | 47.9 | 46.4 | 44.5 | 41.6 | 38.9 | 41. |
|  | 48.6 | 49.7 | 48.4 | 45.7 | 44.1 | 42.8 | 41.5 | 46 |

Drumming Mode -6 ply thick walls

| core | Walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
| 0 | 42.3 | 45.8 | 48.9 | 49.5 | 48.5 | 45.3 | 42.0 | 43.4 | 48.5 |
| 15 | 45.9 | 48.1 | 49.6 | 49.7 | 49.0 | 46.9 | 44.8 | 46.7 | 49.0 |
| 30 | 49.3 | 50.3 | 49.6 | 48.5 | 48.2 | 47.2 | 45.9 | 48.8 | 48.2 |
| 45 | 50.4 | 51.1 | 49.3 | 46.9 | 46.1 | 45.4 | 44.4 | 48.4 | 46.1 |
| 60 | 50.0 | 50.8 | 49.2 | 46.4 | 44.8 | 43.7 | 42.7 | 47.3 | 44.8 |
| 75 | 47.3 | 48.9 | 48.5 | 46.0 | 44.0 | 42.2 | 40.7 | 44.9 | 44.0 |
| 90 | 43.9 | 46.8 | 47.6 | 45.6 | 43.4 | 40.9 | 38.6 | 42.1 | 43.4 |
| 0/90 | 44.3 | 47.6 | 49.5 | 48.6 | 46.9 | 43.8 | 40.9 | 43.2 | 46.9 |
| quasi | 47.0 | 48.7 | 48.4 | 46.0 | 43.9 | 42.1 | 40.5 | 44.6 | 43.9 |

Drumming Mode -8 ply thick walls

| core | Walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
| 0 | 43.1 | 48.4 | 48.9 | 45.6 | 43.4 | 40.6 | 37.1 | 41.9 | 48.7 |
| 15 | 45.8 | 49.5 | 48.4 | 44.6 | 42.5 | 40.4 | 38.0 | 44.0 | 48.7 |
| 30 | 49.2 | 51.0 | 47.0 | 41.4 | 39.6 | 38.5 | 37.3 | 45.6 | 47.9 |
| 45 | 50.9 | 52.0 | 46.5 | 38.3 | 35.5 | 35.0 | 34.3 | 45.2 | 46.5 |
| 60 | 50.6 | 52.1 | 47.1 | 38.2 | 33.3 | 32.1 | 31.5 | 44.0 | 45.6 |
| 75 | 47.9 | 50.9 | 47.4 | 39.2 | 33.3 | 31.0 | 30.0 | 42.0 | 45.1 |
| 90 | 45.1 | 49.8 | 47.4 | 39.5 | 33.5 | 30.8 | 29.3 | 40.1 | 44.8 |
| 0/90 | 45.0 | 50.1 | 49.0 | 43.5 | 39.8 | 37.2 | 34.5 | 41.3 | 47.2 |
| quasi | 49.4 | 51.7 | 48.4 | 41.6 | 38.1 | 36.5 | 35.2 | 44.3 | 47.2 |

## T300/5208 walls / YS90A interlace

Drumming Mode -4 ply thick walls

|  | Walls |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| core | 0 | 15 | 30 | 45 | 60 | 75 |  |  |
|  | 45.1 | 49.5 | 54.5 | 56.5 | 55.7 | 51.4 | 47.1 | 48.2 |
|  | 49.6 | 52.5 | 55.8 | 57.4 | 57.0 | 54.0 | 51.2 | 51.8 |
|  | 54.3 | 56.1 | 57.3 | 57.7 | 57.6 | 56.0 | 54.1 | 55.4 |
|  | 56.4 | 57.9 | 58.1 | 57.4 | 56.9 | 55.6 | 53.9 | 56.0 |
|  | 56.1 | 57.8 | 58.2 | 57.2 | 56.1 | 54.3 | 52.6 | 55.0 |


| 75 | 52.4 | 55.1 | 56.9 | 57.3 | 54.8 | 52.0 | 49.5 | 51.5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 90 | 48.0 | 52.2 | 55.6 | 55.4 | 53.6 | 49.7 | 46.0 | 47.4 |
| 0/90 ${ }_{\text {quasi }}$ | 47.8 | 52.4 | 56.3 | 56.8 | 55.2 | 50.9 | 46.8 | 47.7 |
|  | 52.1 | 54.9 | 56.8 | 56.2 | 54.7 | 51.8 | 45.2 | 51.1 |

Drumming Mode -6 ply thick walls

| core | Walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
| 0 | 45.1 | 49.5 | 51.5 | 56.5 | 55.7 | 51.4 | 47.1 | 47.4 | 55.7 |
| 15 | 49.6 | 52.5 | 55.8 | 57.4 | 57.0 | 54.0 | 51.2 | 51.8 | 57.0 |
| 30 | 54.3 | 56.1 | 57.3 | 57.7 | 57.6 | 56.0 | 54.1 | 55.4 | 57.6 |
| 45 | 56.4 | 57.9 | 58.1 | 57.4 | 56.9 | 55.6 | 53.9 | 56.0 | 56.9 |
| 60 | 56.1 | 57.8 | 58.2 | 57.2 | 56.1 | 54.3 | 52.6 | 55.0 | 56.1 |
| 75 | 52.4 | 55.1 | 56.9 | 56.3 | 54.8 | 52.0 | 49.5 | 51.5 | 54.8 |
| 90 | 48.0 | 52.2 | 55.6 | 55.2 | 53.6 | 49.7 | 46.0 | 47.4 | 53.6 |
| 0/90 | 47.8 | 52.4 | 56.3 | 56.8 | 55.2 | 50.9 | 46.8 | 47.7 | 55.2 |
| quasi | 52.1 | 54.9 | 56.8 | 56.2 | 54.7 | 51.8 | 49.2 | 51.1 | 54.7 |

Drumming Mode -8 ply thick walls

| core | Walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
| 0 | 45.0 | 51.5 | 54.5 | 53.5 | 52.0 | 48.3 | 43.4 | 45.9 | 54.5 |
| 15 | 48.2 | 52.9 | 54.4 | 53.0 | 51.6 | 48.8 | 43.3 | 48.6 | 54.9 |
| 30 | 52.3 | 55.1 | 53.9 | 51.2 | 50.2 | 48.5 | 46.4 | 51.2 | 54.9 |
| 45 | 54.5 | 56.6 | 54.0 | 49.6 | 48.0 | 46.9 | 45.3 | 51.4 | 54.2 |
| 60 | 54.2 | 56.8 | 54.6 | 49.6 | 46.9 | 45.3 | 43.6 | 50.3 | 53.6 |
| 75 | 50.9 | 55.3 | 54.6 | 50.0 | 46.7 | 44.2 | 41.8 | 47.6 | 52.8 |
| 90 | 47.7 | 53.9 | 54.4 | 50.1 | 46.6 | 43.6 | 40.2 | 45.0 | 52.4 |
| 0/90 | 47.3 | 53.8 | 55.3 | 52.4 | 49.9 | 46.5 | 42.2 | 45.5 | 53.7 |
| quasi | 52.5 | 56.0 | 55.2 | 51.5 | 49.3 | 47.2 | 44.8 | 49.8 | 54.3 |

YS90A/25C walls / YS90A interlace

Drumming Mode -4 ply thick walls

| walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| core | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  |
|  | 41.7 | 56.7 | 68.5 | 73.1 | 72.0 | 69.6 | 46.6 | 47.3 |
| 15 | 57.1 | 63.7 | 69.4 | 73.4 | 73.6 | 69.8 | 62.4 | 65.2 |
| 30 | 66.6 | 70.8 | 66.1 | 67.9 | 70.5 | 64.2 | 64.4 | 69.3 |
| 45 | 69.7 | 74.3 | 67.6 | 62.3 | 63.6 | 64.2 | 60.2 | 67.5 |
| 60 | 69.5 | 74.6 | 69.3 | 63.2 | 60.5 | 59.8 | 56.2 | 65.5 |
| 75 | 64.6 | 71.1 | 68.6 | 63.8 | 60.1 | 57.4 | 53.0 | 61.3 |
| 90 | 47.6 | 63.9 | 66.9 | 63.3 | 59.3 | 54.1 | 43.7 | 46.9 |
| 0/90 | 47.6 | 65.3 | 71.9 | 71.4 | 68.7 | 62.8 | 46.1 | 47.6 |
| quasi | 69.5 | 75.7 | 73.7 | 70.9 | 69.4 | 67.0 | 61.6 | 67.3 |

Drumming Mode -6 ply thick walls

| core | walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
| 0 | 42.2 | 57.1 | 69.4 | 72.3 | 73.1 | 63.7 | 47.2 | 47.8 | 71.2 |
| 15 | 56.1 | 63.4 | 70.6 | 74.8 | 74.8 | 69.9 | 62.2 | 64.4 | 73.1 |
| 30 | 67.1 | 72.1 | 71.1 | 72.8 | 74.0 | 72.1 | 66.5 | 70.5 | 74.8 |
| 45 | 71.5 | 76.7 | 73.4 | 71.0 | 71.1 | 69.9 | 65.0 | 70.4 | 74.0 |
| 60 | 71.2 | 76.9 | 74.5 | 71.4 | 69.7 | 67.6 | 62.8 | 68.8 | 71.1 |
| 75 | 64.8 | 72.6 | 73.2 | 70.9 | 68.4 | 64.5 | 58.3 | 63.0 | 69.7 |
| 90 | 48.2 | 65.6 | 71.3 | 69.9 | 67.0 | 59.9 | 46.2 | 48.0 | 68.4 |
| 0/90 | 48.0 | 66.0 | 73.7 | 73.9 | 71.2 | 62.5 | 47.0 | 48.2 | 57.7 |
| quasi | 64.0 | 72.1 | 73.0 | 70.8 | 68.3 | 64.1 | 57.7 | 60.2 | 67.0 |

Drumming Mode -8 ply thick walls

| core | walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
| 0 | 42.6 | 62.8 | 67.5 | 66.5 | 64.9 | 59.7 | 43.7 | 46.9 | 73.2 |
| 15 | 54.1 | 65.0 | 65.3 | 64.5 | 63.7 | 60.3 | 52.1 | 59.0 | 73.6 |
| 30 | 65.5 | 71.3 | 60.4 | 57.6 | 58.9 | 58.1 | 53.5 | 64.6 | 72.7 |
| 45 | 71.0 | 76.4 | 63.0 | 51.5 | 51.7 | 52.6 | 49.8 | 64.7 | 70.7 |
| 60 | 70.7 | 77.3 | 66.7 | 53.9 | 48.2 | 47.7 | 45.6 | 62.9 | 69.6 |
| 75 | 63.1 | 74.7 | 67.9 | 56.9 | 49.0 | 46.0 | 42.6 | 57.3 | 68.8 |
| 90 | 48.6 | 71.8 | 67.9 | 57.8 | 49.6 | 45.6 | 38.3 | 46.4 | 68.1 |
| 0/90 | 48.2 | 72.0 | 70.5 | 63.9 | 59.8 | 55.4 | 42.3 | 46.8 | 72.2 |
| quasi | 67.6 | 76.2 | 68.7 | 60.3 | 57.0 | 55.1 | 50.5 | 62.1 | 71.7 |

Although the T300/5208-T300 interlace material combination provides little margin, layups do exist for each material combination which exceed the 50 Hz minimum. This information will be used with the following thermal and failure analyses, as well as other criteria, to derive the trade-offs that will allow an informed choice for the final design.

### 4.3 THERMAL MODEL

### 4.3.1 MODEL FEATURES

As mentioned in the model overview section above, the SHELL 99 laminate elements used in the structural models are quadratic and do not support thermal conductivity calculations. The SHELL 57 elements, which do support thermal conductivity, are not useful for thermal expansion, do not allow specification of individual laminate layers, and are linear.

Thus a two-part process was necessary for the thermal model. In the first part, the SHELL 57 elements are used, along with appropriate thermal boundary conditions, to determine a steady state temperature distribution. Because these elements can be one material only but must represent laminates whose plies have orthotropic thermal properties, the laminate thermal properties were calculated outside of ANSYS (on an excel spreadsheet) then entered as an equivalent orthotropic material for the elements.

In the second part, the temperature from the calculated thermal distribution was mapped to an identical model in which the SHELL 57 elements had been replaced with SHELL 63 elements. The SHELL 63 elements, which are linear and support thermal expansion and stiffness but do not take laminate layups as inputs, had to be used instead of the SHELL 99 so that the nodes between the two models would correspond. Using the thermal conductivity model's temperature distribution in the thermal expansion model facilitates calculation of thermal distortion, and the resulting deformation of the instrument.


Figure 4-11 Thermal expansion modeling using two models

The thermal boundary conditions in the model are threefold. First, heat is assumed to be generated by the calorimeters and their electronics, and to enter the grid structure by conduction through the calorimeter attachments at the bottom corners of each of the grid cells. Because different types of electronics are mounted on the backs of the calorimeters, different cells add different amounts of heat to the system, as shown below. The calorimeter and TEM boards, mounted in each grid cell, generate 7.4 W and 5.5 W respectively. The SIU and ACD boards, mounted in the corner cells as shown, generate 5 W and 14.5 W respectively.

# Calorimeter and TEMS unit output heat to each cell <br> <br> SIU and ACD <br> <br> SIU and ACD mounted as mounted as shown 

 shown}

| SIU |  |  | ACD |
| :--- | :--- | :--- | :--- |
|  |  |  |  |
|  |  |  |  |
| $A C D$ |  |  | SIU |

Figure 4-12 Locations of grid heat sources

Second, the heat pipes in the aluminum attachment grid and the radiators on the outside of the perimeter panels are assumed to be efficient enough that the temperature at these points is fixed. Nominally this temperature should be zero degrees Celsius. However, since we're interested in thermal distortion of a structure built to exact dimensions in a $25^{\circ}$ environment and the FEM assumes a base temperature of $0^{\circ}$, the temperature will be set to $-25^{\circ}$. This will account for the difference between the ambient temperatures of the assembly and on-orbit environments.

Third, we assume that heat only leaves the structure through the isotropic heat pipes and radiators. Thus there is no loss through radiation either inside or outside the structure and all elements are assumed to be insulated to radiation.

### 4.3.2 RESULTS

## THERMAL CONDUCTIVITY

The three material combinations used in the frequency analysis were once again examined for thermal distortion. Because the thermal properties for T300 and YS90A are dramatically different, the results are easily predictable.

Table 4-7 Conductivity and coefficient of thermal expansion for aluminum and composite materials in $x$ and $y$ directions.

|  | $\mathrm{K}_{\mathrm{x}}\left(\frac{W}{m K}\right)$ | $\mathrm{K}_{\mathrm{y}}\left(\frac{W}{m K}\right)$ | $\alpha_{\mathrm{x}}\left(\frac{\mu m}{C^{\circ}}\right)$ | $\alpha_{\mathrm{y}}\left(\frac{\mu m}{C^{\circ}}\right)$ |
| :--- | :--- | :--- | :--- | :--- |
| Aluminum | $120-240$ | $120-240$ | 33 | 33 |
| T300/5208 <br> prepreg | 4.6 | 0.7 | 0.02 | 22.5 |
| YS90A/25C <br> prepreg | 304 | 0.7 | -1.2 | 25 |

Indeed, the all YS90A model demonstrated very good thermal conductivity compared to an aluminum design (with a $\Delta \mathrm{T}$ of $3.5^{\circ} \mathrm{C}$ ), as shown in the tables below. The thermal path directly from the center of the grid to the outside radiator panels is long enough to build up a high temperature difference, as evidenced by the all $0^{\circ}$ layup. The path from the bottom of the grid to the isothermal heat pipes at the top, however, is much shorter. As long as enough fibers are oriented towards the vertical, maximum temperatures can easily be kept below around $20^{\circ}$ Celsius.

Table 4-8 Maximum $\Delta \mathrm{T}$ (in ${ }^{\circ} \mathrm{C}$ ) across all YS90A grid for different wall thicknesses and combinations of wall and center layups

Walls 4 plies thick

|  | walls |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| center | 0 | 15 | 30 | 45 | 60 | 75 | 900 | /90 |
|  | 131.3 | 45.3 | 20.5 | 12.4 | 9.5 | 8.2 | 7.8 | 12.4 |
| 15 | 93.0 | 32.2 | 16.6 | 11.2 | 8.8 | 7.6 | 7.3 | 11.2 |
| 30 | 86.9 | 25.6 | 13.2 | 9.3 | 7.5 | 6.6 | 6.4 | 9.3 |
| 45 | 86.0 | 24.0 | 11.6 | 8.1 | 6.6 | 5.9 | 5.7 X | XX |
| 60 | 86.3 | 23.6 | 10.9 | 7.5 | 6.1 | 5.5 | 5.3XXX | XXX |
| 75 | 87.1 | 23.6 | 10.7 | 7.3 | 5.9 | 5.3 | 5.1 X | XXX |
| 90 | 87.4 | 23.7 | 10.7 | 7.2 | 5.8 | 5.3 | 5.1 X | XXX |
| 0/90 | 86.0 | 24.0 | 11.6 | 8.1 | 6.6 | 5.9 | 5.7X | XXX |
| quasi | 86.0 | 24.0 | 11.6 | 8.1 | 6.6 | 5.9 | 5.7 X | XXX |

Walls 6 plies thick

|  | walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| center | 0 | - 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
|  | 133.0 | 36.0 | 15.2 | 9.4 | 7.1 | 6.1 | 5.8 | 9.4 | 9.4 |
| 15 | 100.6 | 28.1 | 13.4 | 8.8 | 6.8 | 5.9 | 5.6 | 8.8 | 8.8 |
| 30 | 93.9 | 21.7 | 11.3 | 7.8 | 6.2 | 5.4 | 5.3 | 7.8 | 7.8 |
| 45 | 92.6 | 19.7 | 9.8 | 6.9 | 5.6 | 5.0 | 4.8 | 6.9 | 6.9 |


| 60 | 92.4 | 18.9 | 9.1 | 6.4 | 5.2 | 4.7 | 4.6 | 6.4 | 6.4 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 75 | 92.6 | 18.6 | 8.7 | 6.1 | 5.0 | 4.6 | 4.4 | 6.1 | 6.1 |
| 90 | 92.7 | 18.6 | 8.7 | 6.1 | 5.0 | 4.5 | 4.4 | 5.1 | 6.1 |
| 0/90 | 92.6 | 19.7 | 9.8 | 6.9 | 5.6 | 5.0 | 4.8 | 6.9 | 6.9 |
| uasi | 92.6 | 19.7 | 9.8 | 6.9 | 5.6 | 5.0 | 4.8 | 6.9 | 6. |

Walls 8 plies thick

|  | walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| center | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 quasi |  |  |
|  | 135.8 | 30.1 | 12.2 | 7.7 | 5.8 | 5.0 | 4.8 | 7.7 | 7.7 |
| 15 | 110.0 | 25.8 | 11.5 | 7.4 | 5.7 | 4.9 | 4.7 | 7.4 | 7.4 |
| 30 | 102.6 | 20.2 | 10.3 | 6.9 | 5.4 | 4.7 | 4.5 | 6.9 | 6.9 |
| 45 | 100.8 | 17.8 | 9.2 | 6.3 | 5.0 | 4.5 | 4.3 | 6.3 | 6.3 |
| 60 | 100.2 | 16.8 | 8.4 | 5.9 | 4.8 | 4.3 | 4.1 | 5.9 | 5.9 |
| 75 | 100.1 | 16.3 | 8.1 | 5.7 | 4.6 | 4.2 | 4.0 | 5.7 | 5.7 |
| 90 | 100.1 | 16.2 | 8.0 | 5.6 | 4.6 | 4.1 | 4.0 | 5.6 | 5.6 |
| 0/90 | 100.8 | 17.8 | 9.2 | 6.3 | 5.0 | 4.5 | 4.3 | 6.3 | 6.3 |
| quasi | 100.8 | 17.8 | 9.2 | 6.3 | 5.0 | 4.5 | 4.3 | 6.3 | 6.3 |

Both the models in which T300/5208 prepreg made up the walls however, demonstrate that T 300 is very poor conductor. The temperature differences are so high, as shown in the results of the 4 ply thick T300/5208 wall/YS90A interlace design below, that the assumption of only conductive rather than radiative transfer is no longer valid.

Table 4-9 Maximum $\Delta \mathrm{T}$ (in ${ }^{\circ} \mathrm{C}$ ) across T300/YS90A hybrid grid for four ply thick walls and combinations of wall and center layups

|  | walls |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| center | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  |
|  | 222 | 216 | 202 | 186 | 173 | 165 | 162 | 186 |
| 15 | 215 | 209 | 196 | 181 | 169 | 161 | 158 | 181 |
| 30 | 200 | 195 | 183 | 170 | 159 | 152 | 149 | 170 |
| 45 | 186 | 181 | 170 | 158 | 148 | 142 | 140 | 158 |
| 60 | 175 | 171 | 161 | 149 | 140 | 134 | 132 | 149 |
| 75 | 169 | 165 | 155 | 144 | 135 | 129 | 127 | 144 |
| 90 | 168 | 163 | 153 | 142 | 133 | 128 | 126 | 142 |
| 0/90 | 186 | 181 | 170 | 158 | 148 | 142 | 140 | 158 |
| quasi | 186 | 181 | 170 | 158 | 148 | 142 | 140 | 158 |

## THERMAL DEFORMATION

Besides keeping the electronics from overheating, the primary function of the passive thermal design is to minimize thermal deformation. Keeping temperatures low is a good way to do this, and is the only way when using isotropic materials. Finding the best design is less straightforward for the composite grid, where choice of layup affects both the temperature distribution and thermal expansion.

As an example, consider the YS90A/25C prepreg, which has almost negligible expansion in the fiber direction but expansion similar to aluminum in the transverse direction. A layup in which the fibers are all 0 's would expand vertically with a vertical thermal gradient, but not bend much. A layup in which the fibers are all 90's would have negligible vertical expansion under the same thermal gradient, but would bend because the bottom is hotter than the top. However, as we saw in the previous section, the layup of all 0 's would have a much higher $\Delta \mathrm{T}$ between the bottom and top than the all $90^{\circ}$ layup. In addition to these competing tendencies, the aluminum grid, with it's higher C.T.E., must be considered as well.

The danger of excessive deformation is misalignment of the instrument. The primary concern is that thermal cycling as the spacecraft (in low earth orbit with a $29^{\circ}$ inclination) passes between eclipse and sunlight will cause shifts in the locations of the sensors that can cause errors in instrument performance.


Figure 4-13 Vertical thermal gradient causes concave bowing in aluminum grid
In the all aluminum model, the grid bends inward, causing the gap to narrow by about 0.4 mm . In the design made entirely of YS90A, with it's negative thermal expansion, most of the layup options actually cause the towers to bend outward. The contraction of the gap for the different all YS90A layups is shown below in millimeters.

Table 4-10 Tower gap expansion (in mm) in an all YS90A grid for different wall thicknesses and combinations of wall and center layups
Walls 4 plies thick

|  |  | walls |  |  |  |  |  |  |
| ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| center | 0 | 15 | 30 | 45 | 60 | 75 | 90 | $0 / 90$ |
|  | -0.17 | -0.05 | -0.03 | -0.04 | 0.01 | 0.03 | 0.03 | -0.05 |
| 15 | -0.07 | -0.03 | -0.03 | -0.15 | -0.07 | -0.02 | 0.03 | -0.09 |
| 30 | -0.09 | -0.10 | -0.15 | -0.23 | -0.20 | -0.20 | -0.12 | 0.08 |
| 45 | -0.07 | -0.13 | -0.22 | -0.21 | -0.10 | -0.22 | -0.25 | 0.09 |
| 60 | -0.07 | 0.03 | -0.21 | -0.17 | -0.12 | 0.01 | -0.12 | 0.07 |
| 75 | -0.07 | -0.03 | -0.17 | -0.29 | -0.13 | -0.06 | -0.06 | 0.07 |
| 90 | -0.07 | -0.04 | -0.20 | -0.29 | -0.18 | -0.07 | -0.04 | 0.06 |
| 0 | -0.06 | -0.17 | -0.32 | -0.36 | 0.07 | -0.43 | -0.36 | 0.09 |
| quasi | -0.06 | -0.06 | -0.15 | -0.20 | -0.15 | -0.12 | -0.08 | 0.06 |

Walls 6 plies thick

|  | walls |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| center | 0 | 15 | 30 | 45 | 60 | 75 |  | 0/90 | uasi |
| 0 | -0.17 | -0.03 | -0.03 | -0.09 | -0.02 | 0.03 | 0.04 | -0.12 | -0.01 |
| 15 | -0.08 | -0.03 | -0.08 | -0.16 | -0.08 | -0.04 | -0.02 | -0.13 | -0.05 |
| 30 | -0.07 | -0.06 | -0.18 | -0.22 | -0.25 | -0.19 | -0.15 | -0.26 | -0.16 |
| 45 | -0.07 | -0.12 | -0.23 | 0.02 | -0.28 | -0.31 | -0.25 | -0.33 | -0.20 |
| 60 | -0.07 | -0.06 | -0.25 | -0.32 | -0.14 | -0.16 | -0.17 | -0.34 | -0.16 |
| 75 | -0.07 | -0.02 | -0.21 | -0.43 | -0.21 | -0.11 | -0.08 | -0.40 | -0.15 |
| 90 | -0.07 | -0.03 | -0.24 | -0.40 | -0.27 | -0.09 | -0.07 | -0.41 | -0.11 |
| 0/90 | -0.07 | -0.11 | -0.33 | -0.46 | -0.57 | 0.58 | -0.38 | -0.36 | -0.27 |
| quasi | -0.06 | -0.05 | -0.19 | -0.28 | -0.21 | -0.14 | -0.10 | -0.31 | -0.12 |

Walls 8 plies thick

|  | walls |  |  |  |  |  |  |  |  |  |
| ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |

### 4.4 LOAD MODEL

### 4.4.1 MODEL FEATURES

The model used to model failure under loading, as far as the elements and boundary conditions are concerned, is the same as the model used for frequency analysis. As such, the discussion in section 4.2 applies to this model as well.

The difference is that this model solves the static problem of deformation under a 7.25 g load. Given strength criteria as parameters, the SHELL 99 elements calculate strength ratios for each ply in the laminates they model. Thus the solution can be queried to find the minimum strength ratio for each element and the ply it applies too.

### 4.4.2 RESULTS

Finding the location of the weakest strength ratio is not as easy to automate in ANSYS as finding and recording natural frequencies or thermal gradients and deformations, and a thorough analysis of all 729 designs considered would be very tedious. Fortunately, the combined filters of the frequency and thermal requirements severely curtail the number of designs that must be considered. The best combination of frequency and thermal results is in the case of the all YS90A design with the 6 ply thick walls. Examining the tables of results below, we see that the very best frequency, occurring when the walls are $\pm 15^{\circ}$ and the center is $\pm 60^{\circ}$, has an unacceptably high $\Delta \mathrm{T}$ and tower gap contraction. Similarly, the best $\Delta \mathrm{T}$ 's and gap contractions do not correspond to the higher frequencies. A good compromise, however, is the example of the walls at $\pm 60^{\circ}$ and the center at $\pm 15^{\circ}$, highlighted in bold print. As long as this option has an acceptable safety factor when loaded at 7.25 g , it should be a satisfactory design.

Table 4-11 First mode frequency, thermal gradient, and thermal expansion of the all YS90A design with walls 6 plies thick

First natural frequency $(\mathbf{H z})$

|  | walls |  |  |  |  |  |  |  |  |  |
| :---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| center | 0 | 15 | 30 | 45 | 60 | 75 | 90 |  | $0 / 90$ | quasi |
| 0 | 42.2 | 57.1 | 69.4 | 72.3 | 73.1 | 63.7 | 47.2 | 47.8 | 71.2 |  |
| 15 | 56.1 | 63.4 | 70.6 | 74.8 | 74.8 | 69.9 | 62.2 | 64.4 | 73.1 |  |
|  | 67.1 | 72.1 | 71.1 | 72.8 | 74.0 | 72.1 | 66.5 | 70.5 | 74.8 |  |


| 45 | 71.5 | 76.7 | 73.4 | 71.0 | 71.1 | 69.9 | 65.0 | 70.4 | 74.0 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 60 | 71.2 | 76.9 | 74.5 | 71.4 | 69.7 | 67.6 | 62.8 | 68.8 | 71.1 |
| 75 | 64.8 | 72.6 | 73.2 | 70.9 | 68.4 | 64.5 | 58.3 | 63.0 | 69.7 |
| 90 | 48.2 | 65.6 | 71.3 | 69.9 | 67.0 | 59.9 | 46.2 | 48.0 | 68.4 |
| 0/90 | 48.0 | 66.0 | 73.7 | 73.9 | 71.2 | 62.5 | 47.0 | 48.2 | 57.7 |
| quasi | 64.0 | 72.1 | 73.0 | 70.8 | 68.3 | 64.1 | 57.7 | 60.2 | 67.0 |

## $\operatorname{Max} \Delta \mathrm{T}$ in ${ }^{\circ} \mathbf{C}$

| walls |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| core | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 |  | quasi |
|  | 133.0 | 36.0 | 15.2 | 9.4 | 7.1 | 6.1 | 5.8 | 9.4 | 9.4 |
|  | 100.6 | 28.1 | 13.4 | 8.8 | 6.8 | 5.9 | 5.6 | 8.8 | 8.8 |
|  | 93.9 | 21.7 | 11.3 | 7.8 | 6.2 | 5.4 | 5.3 | 7.8 | 7.8 |
|  | 92.6 | 19.7 | 9.8 | 6.9 | 5.6 | 5.0 | 4.8 | 6.9 | 6.9 |
|  | 92.4 | 18.9 | 9.1 | 6.4 | 5.2 | 4.7 | 4.6 | 6.4 | 6.4 |
|  | 92.6 | 18.6 | 8.7 | 6.1 | 5.0 | 4.6 | 4.4 | 6.1 | 6.1 |
|  | 92.7 | 18.6 | 8.7 | 6.1 | 5.0 | 4.5 | 4.4 | 5.1 | 5.1 |
| 0/90 | 92.6 | 19.7 | 9.8 | 6.9 | 5.6 | 5.0 | 4.8 | 6.9 | 6.9 |
| quasi | 92.6 | 19.7 | 9.8 | 6.9 | 5.6 | 5.0 | 4.8 | 6.9 | 6.9 |

Tower gap contraction (mm)

| walls |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| core | 0 | 15 | 30 | 45 | 60 | 75 | 900/90 quasi |  |  |
|  | -0.17 | -0.03 | -0.06 | -0.09 | -0.02 | 0.03 | 0.04 | -0.12 | -0.01 |
|  | -0.08 | -0.03 | -0.08 | -0.16 | -0.08 | -0.04 | -0.02 | -0.13 | -0.03 |
|  | -0.07 | -0.06 | -0.18 | -0.22 | -0.25 | -0.19 | -0.15 | -0.26 | -0.16 |
|  | -0.07 | -0.12 | -0.23 | 0.02 | -0.28 | -0.31 | -0.25 | -0.33 | -0.20 |
|  | -0.07 | -0.06 | -0.25 | -0.32 | -0.14 | -0.16 | -0.17 | -0.34 | -0.16 |
|  | -0.07 | -0.02 | -0.21 | -0.43 | -0.21 | -0.11 | -0.08 | -0.40 | -0.15 |
|  | -0.07 | -0.03 | -0.24 | -0.40 | -0.27 | -0.09 | -0.07 | -0.41 | -0.11 |
| 0/90 | -0.07 | -0.11 | -0.33 | -0.46 | -0.57 | -0.44 | -0.38 | -0.36 | -0.27 |
| quasi | -0.06 | -0.05 | -0.19 | -0.28 | -0.21 | -0.14 | -0.10 | -0.31 | -0.12 |

An image of the failure results for this model is shown below. The lowest strength ratios were found in the walls, with values as low as 4 around the center pieces and 10 around the interlaced sections. The top layer of interlace at the nodes in the middle of the edge ribs also demand attention. In that region, the node where the shell elements of the interlace intersect returns a very high stress and consequently low strength ratio. This can be corrected by selective reinforcement: a composite patch
applied to the outside of the grid which can span the weaker interlace and spread out the stress.


Figure 4-14 Strength ratios in the chosen design

## CHAPTER 5: EXPERIMENTAL VERIFICATION

For confidence in the predictions of the FEM, it is important to verify the code with a real test specimen. Although considered multiple times, budget constraints and the difficulty of large scale testing precluded construction of a full-scale GLAST test grid. Instead, a smaller scale grid that could be built and tested in the laboratory on campus was used. Although the test specimen is a $3 \times 3$ grid and has different dimensions than the GLAST design, the same FEM code, with only the modification of a few constants, can be used for both of them. If the code models the behavior of the specimen with reasonable accuracy, as indeed it did, we may assume it models the real design reasonably accurately as well.

### 5.1 SPECIMEN DESIGN

The test specimen is a $3 \times 3$ grid of cells, each of which is 16 cm on a side and 11.5 cm deep. The ribs are 7.5 mm across, and are composed of walls 1 mm thick, interlace 2.4 cm deep, and a core making up the interior. The walls are T800 prepreg, the interlace is T300 yarn in a room temperature cure epoxy (fiber volume fraction 0.25 ), and the core is balsa wood.



Figure 5-1 Specimen top view and cross-section

### 5.2 MANUFACTURE

The test specimen was fabricated earlier in the research effort, before the current manufacture method, described in section 2.3 , was developed. Instead of prefabricated ribs slotted together, the technique was to insert tube sections, which would become the walls, into a slotted grid already constructed of the center material. From there, the fabrication is the same, continuing with interlace on one side, cure, then interlace on the other. This technique was later abandoned because of the difficulty of getting consistent tubes and precisely fitting and lining up the pieces.

### 5.3 TESTING

The specimen was tested with both in-plane and out-of-plane loads that could be compared to FEM.

Out of plane loading


In plane loading


Figure 5-2 Experimental verification load cases
Testing was done using an MTS machine measuring applied load and displacement at the loading point. Both tests setups are shown below.


Figure 5-3 Experimental verification bending test


Figure 5-4 Experimental verification compression test

In order to distribute the forces and avoid stress concentrations, the load and support interfaces in the bending test were cylindrical aluminum rods. Load on the in-
plane model was applied to a $1 / 2$ " steel plate that covered only one rib, keeping the primary compression on the one rib while spreading the actual force over a larger surface.

The finite element model of the bending test assumed that of the two supported nodes, one was constrained in $\mathrm{X}, \mathrm{Y}$, and Z as an anchor, and the other was constrained only in Z (the direction of out-of-plane loading), free to move in-plane as the test specimen contact point could move over the cylindrical support.

The finite element model of the in-plane test assumed that the entire bottom side was fixed in $\mathrm{X}, \mathrm{Y}$, and Z . All nodes on the top of the loaded rib were constrained to move together in the direction of loading, and had the load distributed over it appropriately to ensure this.

### 5.4 RESULTS

To compare the FEM and experimental models, a "stiffness" number was calculated for each: the applied force divided by calculated displacement of the loaded point for the FEM, and the slope of the load displacement curve for the experimental results. A sample load displacement curve for the in-plane test is shown below.

## Grid In-Plane Load Test Results



Figure 5-5 Load vs displacement curve for in-plane test

From the test data the stiffness for the bending and in-plane tests, respectively, is $204 \mathrm{KN} / \mathrm{m}$ and $39 \mathrm{MN} / \mathrm{m}$. The difficulty of matching this to the FEM is that some design parameters are not known exactly and can only be guessed at. The fiber volume fraction of the interlace, which can theoretically vary between 0 and $50 \%$, is the primary unknown. Imperfections in the composite tubes used caused the width of some of the ribs to vary by as much as $15 \%$ over their length. Additionally, misalignment during the machining to make the top and bottom sides of the grid parallel resulted in an interlace depth varying as much as $\pm 14 \%$ between extreme corners of the grid.

To take into account these unknowns, best guesses were entered into the FEM and perturbed until both models had similar error magnitudes. Assuming an average interlace depth of 2.3 cm , wall width of 0.9 mm , and fiber volume fraction of $25 \%$ yields an FEM that agrees with both bending and in-plane results within $25 \%$.

## CHAPTER 6: PROPOSED DESIGN

The satisfactory design developed in the previous sections is summarized here with references to sections where more details can be found. The basic parameters of the composite GLAST grid (dimensions, materials, layups) are presented first, followed by its manufacture process. Subsequently, the design is compared to the baselined aluminum design used as a guide for the composite design, and to the aluminum design as it has evolved in the year since the two designs began diverging.

### 6.1 PARAMETERS

The major component of the grid is the composite grid, which is a $4 \times 4$ array of cells each 37.2 cm on a side and 24 cm tall, with 6 mm wide ribs. It is manufactured using the slotted TRIG technique described in Section 2.3. As derived in Section 3.3 , the walls are 1.5 mm thick, the center 3 mm thick, and both are made of unidirectional YS90A/25C prepreg. The wall and center layups are $\pm 15^{\circ}$ and $\pm 60^{\circ}$ angle plies, respectively.


Figure 6-1 Geometry, materials, and layups for GLAST grid design
As described in Section 3.3 , there will be three additional aluminum pieces: a flange on the top of the composite grid with embedded heat pipes and through holes for
mounting the towers, brackets to hold the calorimeters, and bosses for attaching the ACD and spacecraft adapter.

### 6.2 MANUFACTURE

Manufacture begins with fabrication of the ribs for the slotted TRIG assembly. Wall and center pieces are layed up together for co-cure with the planned interlace areas kept free with removable inserts.


Figure 6-2 Layup of ribs
The four ribs that will have the spacecraft mounting bosses attached to their ends are layed up with additional inserts reserving space for the bosses to be bonded into.


Assembled ribs accommodate plug-in bosses


Figure 6-3 Modification for attachment of spacecraft adapter mounting bosses
After the ribs are cured, the inserts are left in while the slots are waterjet cut, then removed before assembly of the ribs into a grid. At this stage the through holes for the calorimeter brackets are drilled.


Figure 6-4 Cutting slots into ribs
Because the spacecraft mounting bosses require all outside ribs to have slots facing down, the ribs must be cut and assembled as shown below.


Figure 6-5 Rib assembly with proper slot orientation
The assembled grid is then placed in a fixture to square the corners of the grid and align it properly. The top is then interlaced. Pegs in the fixture are used to increase tension on and straighten the fibers.


Figure 6-6 Interlace of top side of grid
After the top has been interlaced, the spacecraft adapter bosses can be inserted, the grid turned over, and the bottom interlaced as well.


Figure 6-7 Insertion of aluminum spacecraft adapter mounting bosses


Figure 6-8 Interlace of bottom side of grid

### 6.3 COMPARISON TO ALUMINUM GRID

As stated in the introduction, the composite design is an alternative to a baselined aluminum design. Because the composite grid is based off of an aluminum design frozen a year ago, but which has continued to evolve, there are two comparisons possible, one to the past aluminum design and the other to the current design. Although the fitness of each design to meet the fundamental requirements can be compared, there are many differences in their contexts which make comparison difficult or suspect. The old aluminum design is simply the composite with aluminum substituted. It has since been changed to make it better, and does not represent the best that aluminum has to offer. The new design uses slightly different requirements, and relies upon stiffening not considered in the first design. With these warnings in mind, the table below compares the predicted performance of the three designs in terms of first natural frequency, the factor that the launch load could be increased before failure, the temperature gradient through the grid thickness, the contraction between the towers when operating at steady state, and the mass including attachments.

Table 6-1 Comparison of predicted performance for composite design, old aluminum design, and current aluminum design

| Manufacture <br> Technique | Carbon Fiber <br> Composite built <br> up using Slotted- <br> TRIG process | Aluminum <br> machined from <br> $1.5 \mathrm{~m} \mathrm{X} \mathrm{1.5} \mathrm{X}$ <br> 0.2 m solid slab | Aluminum <br> (current) |
| :--- | :--- | :--- | :--- |
| First Natural <br> Frequency | 76 Hz | 48 Hz | 55 Hz |
| Strength Ratio for <br> Launch Load | 4 | 5 | - |
| Max Temperature <br> Difference | $7{ }^{\circ} \mathrm{C}$ | $3.5^{\circ} \mathrm{C}$ | $2.5^{\circ} \mathrm{C}$ |
| Tower Gap <br> Contraction | -0.1 mm | 0.4 mm | - |
| Total Mass with <br> Attachments | 75 kg | 105 kg | 136 kg |

On the balance, the composite design compares quite well. The natural frequency and strength ratio are well above the minimum requirements, providing a margin to work with as the design progresses, whereas the aluminum designs barely meet the natural frequency requirement. The composite grid will have a higher thermal gradient, but the difference is not significant for operation of the electronics. The magnitude of steady state thermal deformation is smaller in the composite design, which implies that the important thermal property, magnitude of transient deformations, will be smaller as well. Finally, the mass of the composite grid is smaller than both aluminum designs.

The relative importance of the design guidelines may vary as the mission design evolves, but in most cases the composite option appears superior. Although saving 60 kilograms on an instrument which masses almost 2 tons may prove inconsequential, increasing the first natural frequency by $50 \%$ and reducing the susceptibility to thermal distortion by a factor of 4 is worth considering. Ultimately, when economics and logistics are taken into account, the composite option may still be the better design. Indeed, if the mission requirements become more strict, it may be the only possible design.

## REFERENCES

S. W. Tsai. Introduction to Composite Materials. Technomic Publishing Co. Lancaster. 1980.
A. Carpinteri. Structural Mechanics, A Unified Approach. E \& FN. New York. 1997
W. Larson, J. Wertz. Space Mission Analysis and Design. Microcosm Inc. Torrance. 1995.

## APPENDIX A: FEM CODE

The modal, failure, and thermal analyses of the grid referred to in the text were all done using ANSYS, a popular finite element modeling package. Because a large number of very similar models needed to be solved for the parametric studies, programs were written for ANSYS that could cycle through many cases. The three programs, including extensive in-line documentation, follow.

## A. 1 STIFFNESS ANALYSIS PROGRAM

```
/COM,ANSYS RELEASE 5.6 UP19991022 19:29:20 04/12/2000
/PREP7
/COM A GLAST MODEL THAT INCLUDES SLOTS AND LAMINATES
! 11/28/00 - Michael Hicks
! This program accepts a number of variable inputs that define
! a composite grid made using the slotted TRIG technique. For
! GLAST the program has the option to include the stiffness of
! an aluminum heat pipe grid and the bottom tray of the tracker
! towers.
! After assembling the model, it loops through possible layup options,
! characterizing the STIFFNESS by recording the first three natural
! modes and frequencies for each design
! All units are SI: meters, kilograms, pascals, etc.
! Note that ilz is often used as an abbreviation for interlace
! Define Boolean variables
TRUE = 1
FALSE = 0
/COM DEFINE THE MODEL
! Grid parameters
CELL_X=4 ! Number of grid cells in the x direction
CELL_Y=4 ! Number of grid cells in the y direction
INCLGRID=TRUE ! Include the aluminum grid or not
INCLTPPN=TRUE ! Include the top panel or not
MASSES=TRUE ! Include the tower and cal masses or not
! Boundary conditions
EIGHTUZ=TRUE ! Use 8 points free in all but z direction
FOURUZ=FALSE ! Use 4 mid-side points free in all but z direction
! Meshing
ELM_WIDE=4 ! Number of elements across the main section of the panel
ILZ_TALL=2 ! Number of elements up the ilz sections
NLZ_TALL=4 ! Number of elements up the nilz sections
```

```
! Geometry
PAN_WIDE=.372 ! Panel width
PAN_TALL=.24 ! Panel height
ILZ_DEEP=.03 ! Interlace height
! Layup
! A cross-section of the panel (a rib of the grid)
! on its side would look like:
```



```
PLY_THCK=.00025 ! Cured ply thickness
```

PLY_THCK=.00025 ! Cured ply thickness
NUM_PLYS=24 ! Number of plies through the entire panel thickness
NUM_PLYS=24 ! Number of plies through the entire panel thickness
WLL_PLYS=6 ! Number of plies in a wall (panel is wall:ilz:wall)
WLL_PLYS=6 ! Number of plies in a wall (panel is wall:ilz:wall)
CORENGL1=45 ! Angle for one of two alternating layers for the core section
CORENGL1=45 ! Angle for one of two alternating layers for the core section
CORENGL2=-45! Angle for one of two alternating layers for the core section
CORENGL2=-45! Angle for one of two alternating layers for the core section
WALLNGL1=45 ! Angle for one of two alternating layers for the wall section
WALLNGL1=45 ! Angle for one of two alternating layers for the wall section
WALLNGL2=-45! Angle for one of two alternating layers for the wall section
WALLNGL2=-45! Angle for one of two alternating layers for the wall section
! Top aluminum flange (included if INCLGRID = TRUE)
! Top aluminum flange (included if INCLGRID = TRUE)
TOP_WIDE=.0254 ! Top flange width
TOP_WIDE=.0254 ! Top flange width
TOP_TALL=.0204 ! Top flange height - 25.4 mm minus 5 mm to approx
TOP_TALL=.0204 ! Top flange height - 25.4 mm minus 5 mm to approx
! hollow heat pipe
! hollow heat pipe
! Additional calculated geometry
! Additional calculated geometry
PAN_THCK=NUM_PLYS*PLY_THCK ! Panel thickness
PAN_THCK=NUM_PLYS*PLY_THCK ! Panel thickness
MN_WIDE=PAN_WIDE-PAN_THCK ! Width of main meshing area

```
MN_WIDE=PAN_WIDE-PAN_THCK ! Width of main meshing area
```

/COM REAL CONSTANTS DEFINED
! Make real constants for masses (kg)
CAL_MASS $=102.6$
! Calorimeter mass
TOW_MASS $=32.6$ ! Tower mass
TPEMASS=TOW_MASS/((ELM_WIDE*2+1)*4) ! Top edge mass
BTCRMASS=CAL_MASS/8 ! 1/8th of the calorimeter mass

```
/COM MATERIALS DEFINED
! Make Material 1 as Aluminum
UIMP,1,EX, , ,76E9,
UIMP,1,KXX, , , 240,
! YS90A/25C prepreg
UIMP,3,EX,EY,EZ,520E9,5.7E9,5.7E9,
UIMP, 3, PRXY,PRYZ,PRXZ,.3,.3,.3,
UIMP, 3,NUXY,NUYZ,NUXZ, , , ,
UIMP, 3, GXY,GYZ,GXZ,5.1E9,3.195E9,3.195E9,
UIMP, 3,ALPX,ALPY,ALPZ,14.78E-6,14.78E-6,22.5E-6,
UIMP,3,DENS, , ,1750,
! Create failure criteria for YS90 prepreg
```

```
TB,FAIL,3,1 ! For material 3 with only 1 temperature
TBTEMP,,CRIT ! The next values are a failure criterion
TBDATA,1,0,0,2 ! Use Tsai-Wu failure criterion
TBTEMP,0 ! At standard 0 temperature
TBDATA,10,1860E6 ! Max X Tensile Strength
TBDATA,11,-350E6 ! Max X Compressive Strength
TBDATA,12,33E6 ! Max Y Tensile Strength
TBDATA, 13,-256E6 ! Max Y Compressive Strength
TBDATA,14,33E6 ! Max Z Tensile Strength
TBDATA,15,-256E6 ! Max Z Compressive Strength
TBDATA,16,59E6 ! Max XY shear
TBDATA,17,59E6 ! Max YZ shear (although I have no data for it)
TBDATA,18,59E6 ! Max ZX shear
TBDATA,19,-1 ! XY coupling constant
TBDATA,20,-1 ! YZ coupling constant
TBDATA,21,-1 ! ZX coupling constant
! YS90A interlace .4 vf (Externally calculated)
UIMP, 4, EX, EY, EZ, 354.1E9,5.1641E9,5.1641E9,
UIMP, 4, PRXY,PRYZ, PRXZ,.496, .3, .3,
UIMP, 4,NUXY,NUYZ,NUXZ, , , ,
UIMP, 4,GXY,GYZ,GXZ, 2.89E9,1.37E9,2.89E9,
UIMP , 4,ALPX,ALPY, ALPZ,-1.129E-6,60E-6, 60E-6,
UIMP,4,DENS, , ,2060,
! Core material in Towers - aluminum honeycomb
UIMP,5,EX,EY,EZ,2.7E9,2.7E9,2.7E9,
UIMP, 5, PRXY, PRYZ, PRXZ,.3,.3,.3,
UIMP, 5, NUXY, NUYZ, NUXZ, r, ,
UIMP, 5,GXY, GYZ, GXZ, 2.62E3,3.26E9,1.9E9,
UIMP,5,ALPX, ALPY, ALPZ,.02E-6, 22.5E-6, 22.5E-6,
UIMP,5,DENS, , ,16,
! Give names to the material numbers so it's easier to see
! what I'm doing
MAT_ALUM=1
MAT_TPAN=2
MAT_T300=3 ! This is actually YS90 but I didn't bother changing
    ! the names through all the following sections
MAT_ILZ=4
MAT_CORE=5
/COM DEFINE ELEMENTS
! Create mass element
ET,1,MASS21
! Make it not have a rotational inertia
KEYOPT,1,2,0
KEYOPT,1,3,2
! Create 3 node beam element
ET, 2, BEAM189
! Create linear-layered shell element
ET, 3,SHELL99
! Create thermal shell element
! ET, 3,SHELL57
/COM CREATE REAL CONSTANTS DESCRIBING LAMINATES
! Non-interlaced (Nilz) section of the panel real constant
R_NILZ = 1
```

```
R,1
RMODIF,1,1,NUM_PLYS,0,0,0,0,0
! Each of these is a layer defined by material, angle, thickness
RMODIF,1,13,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,19,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,22,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,25,MAT_T300,0,PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
!
RMODIF,1,31,MAT_T300,45,PLY_THCK,
RMODIF,1,34,MAT_T300,-45,PLY_THCK,
RMODIF,1,37,MAT_T300,45,PLY_THCK,
RMODIF,1,40,MAT_T300,-45,PLY_THCK,
RMODIF,1,43,MAT_T300,90,PLY_THCK,
RMODIF,1,46,MAT_T300,90,PLY_THCK,
RMODIF,1,49,MAT_T300,90,PLY_THCK,
RMODIF,1,52,MAT_T300,90,PLY_THCK,
RMODIF,1,55,MAT_T300,-45,PLY_THCK,
RMODIF,1,58,MAT_T300,45,PLY_THCK,
RMODIF,1,61,MAT_T300,-45,PLY_THCK,
RMODIF,1,64,MAT_T300,45,PLY_THCK,
!
RMODIF,1,67,MAT_T300,0,PLY_THCK,
RMODIF,1,70,MAT_T300,0,PLY_THCK,
RMODIF,1,73,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,76,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,79,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,82,MAT_T300,WALLNGL1,PLY_THCK,
! Interlaced (Ilz) section of the panel real constants
R_ILZ=2
R,2
RMODIF,2,1,2*WLL_PLYS+1,0,0,0,0,0
! Each of these is a layer defined by material, angle, thickness
RMODIF,2,13,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,19,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,22,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,25,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,28,MAT_T300,WALLNGL1,PLY_THCK,
!
RMODIF,2,31,MAT_ILZ,0,(NUM_PLYS-2*WLL_PLYS) *PLY_THCK,
!
RMODIF,2,34,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,37,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,40,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,43,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,46,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,49,MAT_T300,WALLNGL1,PLY_THCK,
! Interlace-only (no enclosing walls) real contants
R_ILZN=3
R,3
RMODIF,3,1,1,0,0,0,0,0
RMODIF,3,13,MAT_ILZ,0, (NUM_PLYS-2*WLL_PLYS) *PLY_THCK,
```

```
! Tower bottom panels. These are honeycomb core sandwiches
R_TOW=4
R,4
! Each of these is a layer defined by material, angle, thickness
RMODIF,4,1,13,0,0,0,0,0
RMODIF,4,13,MAT_T300,0,.000225/6,
RMODIF,4,16,MAT_T300,60,.000225/6,
RMODIF,4,19,MAT_T300,-60,.000225/6,
RMODIF,4,22,MAT_T300,-60,.000225/6,
RMODIF,4,25,MAT_T300,60,.000225/6,
RMODIF,4,28,MAT_T300,0,.000225/6,
!
RMODIF, 4, 31,MAT_CORE,0,.034-2*.000225,
!
RMODIF,4,34,MAT_T300,0,.000225/6,
RMODIF,4,37,MAT_T300,60,.000225/6,
RMODIF,4,40,MAT_T300,-60,.000225/6,
RMODIF,4,43,MAT_T300,-60,.000225/6,
RMODIF,4,46,MAT_T300,60,.000225/6,
RMODIF,4,49,MAT_T300,0,.000225/6,
! Mass element real constants
R_CAL=5
R,5,BTCRMASS
R_TOWER=6
R,6,TPEMASS
R_BEAM=7
R,7, , , , ,
! Beam Cross-section
SECTYPE, 1, BEAM, RECT, topflange
SECOFFSET, USER, 0, TOP_WIDE/2
SECDATA,TOP_TALL,TOP_WIDE,0,0,0,0,0,0,0,0
/COM ESTABLISH LABELS TO KEEP TRACK OF NUMBERS
! Note that I later found that ANSYS has an automatic way of doing this
NEWKP = 1 ! New keypoint
NEWND = 1 ! New node
NEWLN = 1 ! New line
NEWAR = 1 ! New area
NEWEL = 1 ! New element
NEWND = 1 ! New node
/COM ***************************************
/COM **** MAKE GRID BY CELL WALL PANELS ****
/COM ***************************************
! This section produces a group of meshed areas representing a single
! panel as diagrammed below
interlace only -> | | walls and interlace |
```

```
!
! +--------------------------
! By copying and connecting the areas we create any entire rib
! which is then copied to produce the composite grid
/COM ESTABLISH KEYPOINTS
NUMSTR,KP,NEWKP
! This is the bottom row
K, 0,0,0
K, ,PAN_THCK/2,0,0
K,,PAN_WIDE-PAN_THCK/2,0,0
K,,PAN_WIDE,0,0
NUMSTR,LINE,NEWLN
! Make lines along the bottom row.
L, NEWKP, NEWKP+1,1
L,NEWKP+1,NEWKP+2,ELM_WIDE
L,NEWKP + 2,NEWKP + 3,1
! Copy this row up three times to get horizontal lines for one panel,
LGEN, 2,NEWLN,NEWLN+2,1,0,0,ILZ_DEEP
LGEN, 2, NEWLN, NEWLN+2,1,0,0,PAN_TALL/2
LGEN,2,NEWLN,NEWLN+2,1,0,0,PAN_TALL-ILZ_DEEP
LGEN, 2,NEWLN,NEWLN+2,1,0,0,PAN_TALL
KP1 = NEWKP ! Remember what the first keypoint was
NEWKP = NEWKP + 20 ! New new keypoint
! This is the vertical column of KP's
NUMSTR,KP,NEWKP
K,,0,0,ILZ_DEEP
K, ,0,0,PAN_TALL/2
K, 0,0,PAN_TALL-ILZ_DEEP
K, , 0,0,PAN_TALL
! Make lines along side
L, KP 1,NEWKP,ILZ_TALL
L,NEWKP,NEWKP+1,NLZ_TALL/2
L,NEWKP+1,NEWKP+2,NLZ_TALL/2
L,NEWKP+2,NEWKP+3,ILZ_TALL
! Copy this column sideways three times to get vertical lines for one panel,
LGEN,2,NEWLN+15,NEWLIN+19,1,PAN_THCK/2,0,0
LGEN, 2,NEWLN+15,NEWLIN+19,1,PAN_WIDE-PAN_THCK/2,0,0
LGEN, 2,NEWLN+15,NEWLIN+19,1,PAN_WIDE,0,0
! Merge keypoints
NUMMRG,KP,
NEWKP = KP1 + 20
! Move the keypoints a little near the point where the ribs contact
! in the middle of the slots so that the nodes created there
! will not overlap. Move them 1/1000th of the panel height.
KMODIF,KP1+8,0,0,PAN_TALL/2+PAN_TALL*.001
```

```
KMODIF,KP1+11,PAN_WIDE,0,PAN_TALL/2+PAN_TALL*.001
! Now make the areas that will have only interlace and
! assign the proper elements, etc to them.
NUMSTR,AREA, NEWAR
AL, NEWLN,NEWLN+19,NEWLN+3,NEWLN+15
AL,NEWLN+2,NEWLN+27,NEWLN+5,NEWLN+23
AL,NEWLN+9,NEWLN+22,NEWLN+12,NEWLN+18
AL,NEWLN+11,NEWLN+30,NEWLN+14,NEWLN+26
ASEL, S,AREA, NEWAR,NEWAR+3
AATT,MAT_ILZ,R_ILZ,3,
! Temporarily use ilz rather than ilzn
! Then the areas that will have interlace and walls.
AL, NEWLN+1,NEWLN+23,NEWLN+4,NEWLN+19
AL,NEWLN+10,NEWLN+26,NEWLN+13,NEWLN+22
ASEL,S,AREA, ,NEWAR+4,NEWAR+5
AATT,MAT_ILZ,R_ILZ,3,0
! Then the non-interlaced areas
AL,NEWLN+4,NEWLN+24,NEWLN+7,NEWLN+20
AL,NEWLN+7,NEWLN+25,NEWLN+10,NEWLN+21
AL,NEWLN+6,NEWLN+21,NEWLN+9,NEWLN+17
AL, NEWLN+8,NEWLN+29,NEWLN+11,NEWLN+25
ASEL,S,AREA, NEWAR+6,NEWAR+9
AATT,MAT_NILZ,R_NILZ,3,
! Cut out the lines where the slots are
LDELE, NEWLN+16,
LDELE,NEWLN+28,
! Compress line numbers and figure out what the next NEWLN should be
NUMCMP,LINE
/COM COPY WALL TO PRODUCE OPPOSITE WALL OF CELL
ALLSEL,ALL,ALL
! For some strange reason I have to subtract 1 from the number
! I would have put on the itimes value in the x copy command
AGEN, 2,NEWAR,NEWAR+9,,0,PAN_WIDE,0
/COM NOW DUPLICATE THESE TO FORM Y DIRECTION WALLS
! This is accomplished by spinning them around the xy axis so
! the slots wind up in the right place
! move the work-plane from the bottom up to the top of the grid
wpof,,,PAN_TALL
! rotate it 180 about the x axis then -90 about the z axis
wpro,0,180,0
wpro,-90,0,0
! create coordinate system number 11 on the workplane
! CSWPLA,11,0,1,1
! make the workplane the active system
CSYS,4
! now make a copy of all areas from the new coordinate system to global (0)
ALLSEL,ALL,ALL
ATRAN, 0,ALL, , , 0,0
! Put the workplane back to the global coords and make it current
WPCSYS,-1,0
```

```
CSYS,0
! Merge keypoints, making sure that the keypoints in the middle of the slot
! are not merged.
! NUMMRG,ALL,PAN_TALL*.0001,
! Update the other NEW things
NEWAR = NEWAR+40
NEWKP = KP1 + 80
NEWLN = NEWLN + 120
*IF,INCLTPPN,EQ,TRUE,THEN ! If we want top panels, execute this code.
/COM ************************************************************
/COM **** IF THE TOWER PANELS (OR A SKIN) IS TO BE INCLUDED ****
/COM *************************************************************
/COM NOW ADD THE TOP PANEL (BOTTOM PANEL OF THE TOWER).
! Assign new keypoints from the right number
NUMSTR,KP,NEWKP
K,,0,0,PAN_TALL
K,,PAN_THCK/2,0,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,0,PAN_TALL
K, ,PAN_WIDE,0,PAN_TALL
K, ,0,PAN_THCK/2,PAN_TALL
K,,PAN_THCK/2,PAN_THCK/2,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,PAN_THCK/2,PAN_TALL
K,,PAN_WIDE,PAN_THCK/2,PAN_TALL
K,,0,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,PAN_THCK/2,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,PAN_WIDE,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,0,PAN_WIDE,PAN_TALL
K,,PAN_THCK/2,PAN_WIDE,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,PAN_WIDE,PAN_TALL
K,,PAN_WIDE,PAN_WIDE,PAN_TALL
! Make the lines starting at the right number
NUMSTR,LINE,NEWLN
L,NEWKP+1,NEWKP+2,ELM_WIDE
L,NEWKP+2,NEWKP + 6,1
L,NEWKP+6,NEWKP+5,ELM_WIDE
L, NEWKP+5,NEWKP+1,1
L, NEWKP + 4,NEWKP +5,1
L,NEWKP+5,NEWKP+9,ELM_WIDE
L, NEWKP +9,NEWKP +8,1
L,NEWKP+8,NEWKP+4,ELM_WIDE
L, NEWKP+6, NEWKP + 7, 1
L,NEWKP+7,NEWKP+11,ELM_WIDE
L,NEWKP+11,NEWKP+10,1
L,NEWKP+10,NEWKP+6,ELM_WIDE
L,NEWKP+9,NEWKP+10,ELM_WIDE
L,NEWKP+10,NEWKP+14,1
```

```
L,NEWKP+14,NEWKP+13,ELM_WIDE
L, NEWKP+13,NEWKP+9,1
! Now make the areas
NUMSTR,AREA,NEWAR
AL, NEWLN, NEWLN+1,NEWLN+2,NEWLN+3
AL,NEWLN+4,NEWLN+5,NEWLN+6,NEWLN+7
AL, NEWLN+8,NEWLN+9, NEWLN+10,NEWLN+11
AL,NEWLN+12,NEWLN+13,NEWLN+14,NEWLN+15
AL,NEWLN+2,NEWLN+5,NEWLN+11,NEWLN+12
! Specify elements for panels
ASEL, S,AREA, NEWAR, NEWAR+4
AATT,MAT_CORE,R_TOW, 3,
*ENDIF ! End of top panel code
NEWKP = NEWKP + 12
NEWLN = NEWLN + 16
NEWAR = NEWAR + 5
/COM COPY CELLS TO MAKE GRID PANEL
/COM THIS COPIES THE AREAS
ALLSEL,ALL,ALL
! Copy
AGEN, CELL_X,ALL, , ,PAN_WIDE, 0,0, ,1
ALLSEL,ALL,ALL
AGEN,CELL_Y,ALL, , 0,PAN_WIDE,0, ,1
NEWKP = NEWKP*CELL_X*CELL_Y+1
NEWLN = NEWLN*CELL_X*CELL_Y+1
NEWAR = NEWAR*CELL_X*CELL_Y+1
NUMMRG,KP,PAN_TALL*.0001
/COM MESH THE AREAS
! Use mapped meshing so our line specs will stick
MSHKEY,1
! Mesh all areas
AMESH,ALL
! To be safe, we can put the new nodes and element numbers well ahead
NEWEL =
(CELL_X)* (CELL_Y) * (4* (ELM_WIDE+2) * (2*ILZ_TALL+NLZ_TALL) + (ELM_WIDE+2) * (ELM_WIDE+
2))
NEWND = NEWEL*8
```

```
*IF,MASSES,EQ,TRUE,THEN ! If we want masses, run this code.
/COM ******************************************
/COM **** ADD TOWER AND CALORIMETER MASSES ****
/COM ********************************************
! This section places calorimeter masses at the corners of each grid
! cell where they would be attached, and tower masses along the top
! perimeter of the cell where the towers would be attached
```

```
/COM MESH KEYPOINTS THAT SHOULD HAVE MASSES
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the old KPs)
NUMSTR,KP,NEWKP
K,,PAN_THCK/2,0,ILZ_DEEP
K,,(PAN_WIDE-PAN_THCK/2),0,ILZ_DEEP
K,,PAN_THCK/2,PAN_WIDE,ILZ_DEEP
K,,(PAN_WIDE-PAN_THCK/2),PAN_WIDE,ILZ_DEEP
K,,0,PAN_THCK/2,ILZ_DEEP
K,,0,(PAN_WIDE-PAN_THCK/2),ILZ_DEEP
K,,PAN_WIDE,PAN_THCK/2,ILZ_DEEP
K,,PAN_WIDE,(PAN_WIDE-PAN_THCK/2),ILZ_DEEP
! Select all the keypoints and specify that mass elements will be
! generated off them
ALLSEL,ALL,KP
KATT,MAT_ALUM, R_CAL,1
! Mesh only the keypoints we just made
KMESH,NEWKP,NEWKP+7
! Merge them with previous keypoints so all will be attached to areas
! NUMMRG,KP,PAN_TALL*.0001,
/COM SPECIFY TOWER MASSES
! How many keypoints are there so far? At most this many
NEWKP = NEWKP + 8
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR,KP,NEWKP
K,,PAN_THCK/2,0,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP,,,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,0,1, ,
NEWKP2 = NEWKP +2*ELM_WIDE+1
NUMSTR,KP,NEWKP2
K,,PAN_THCK/2,PAN_WIDE,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP2,,,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,0,1,,
NEWKP2 = NEWKP +2*(2*ELM_WIDE+1)
NUMSTR,KP,NEWKP2
K, ,0,PAN_THCK/2,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP2,,,0,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,1,,
NEWKP2 = NEWKP+3*(2*ELM_WIDE+1)
NUMSTR,KP,NEWKP2
K,,PAN_WIDE,PAN_THCK/2,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP2,,,0,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,1,,
! Select all the keypoints and specify that mass elements will be
! generated off them
ALLSEL,ALL,KP
KATT,MAT_ALUM, R_TOWER,1
! Mesh the ones we want meshed
KMESH,NEWKP,NEWKP + 4* (2*ELM_WIDE+1)
! Merge them with previous keypoints so all will be attached to areas
! NUMMRG,KP,PAN_TALL*.0001,
! Copy the mass elements (only)
ESEL,S,TYPE, ,1
EGEN,CELL_X,4*(4+(ELM_WIDE*2+1)+2),ALL,,r,r,, ,PAN_WIDE,0,0
! 4 walls*(4nodes on ilz+nodes on main panel+calorimeter masses)
ESEL,S,TYPE,,1
EGEN,CELL_Y,CELL_X*4*(4+(ELM_WIDE*2+1)+2),ALL,r,r,r,,0,PAN_WIDE,0
```

```
! Update element and keypoint counter
NEWEL = NEWEL + CELL_Y*CELL_X*4* (4+(ELM_WIDE*2+1) + 2)
NEWKP = NEWKP + 4*(4+(ELM_WIDE*2+1) +2)
NEWND = NEWND + CELL_Y*CELL_X*4*(4+(ELM_WIDE*2+1) +2)
*ENDIF ! End of code that adds masses
```

```
*IF,INCLGRID,EQ,TRUE,THEN ! If we want an aluminum grid, execute this code
/COM ****************************************************************
/COM *** MAKE AN ALUMINUM GRID ON THE TOP OF THE COMPOSITE GRID ***
/COM **************************************************************
! The aluminum flange at the top of the grid cells provides an attachment point
! for the towers, something to contain the heat pipes, and adds stiffness
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR,KP,NEWKP
! First do the x direction
! Keypoints
K,,0,0,PAN_TALL
K, ,PAN_THCK/2,0,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,0,PAN_TALL
K,,PAN_WIDE,0,PAN_TALL
! Lines
NUMSTR,LINE,NEWLN
L, NEWKP,NEWKP+1,1
L,NEWKP+1,NEWKP+2,ELM_WIDE
L,NEWKP + 2,NEWKP + 3,1
! Orientation keypoint
K,,PAN_WIDE/2,0,0
! Select lines and assign them properties and orientation keypoints
LSEL, ,LINE, NEWLN,NEWLN+2, ,,
LATT,MAT_ALUM, R_BEAM, 2, ,NEWKP+4, ,1
! Mesh the lines
NUMSTR,ELEM,NEWEL
NUMSTR,NODE,NEWND
LMESH,NEWLN,NEWLN+2, ,
! Now copy the elements
ESEL,S,ELEM, NEWEL,NEWEL+2+ELM_WIDE-1,,
EGEN, CELL_X, (2+ELM_WIDE) * 3+1,ALL, , , , , , ,PAN_WIDE, 0,0
ESEL,S,ELEM, NEWEL,NEWEL+(2+ELM_WIDE) *CELL_X-1, ,
EGEN, CELL_Y+1,CELL_X*((2+ELM_WIDE)*3+1),ALL,r,r,r,,0,PAN_WIDE,0
NEWEL = NEWEL + ((CELL_Y+1)*CELL_X)* (1+2* (2+ELM_WIDE))
NEWND = NEWND + ((CELL_Y+1)*CELL_X)*(1+3*(2+ELM_WIDE)) +1
! Now do the y direction
! Keypoints
NEWKP = NEWKP+5
NUMSTR,KP,NEWKP
K,,0,0,PAN_TALL
K,,0,PAN_THCK/2,PAN_TALL
K, ,0,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,0,PAN_WIDE,PAN_TALL
! Lines
```

```
NEWLN = NEWLN+3
NUMSTR, LINE,NEWLN
L, NEWKP,NEWKP +1,1
L,NEWKP+1,NEWKP+2,ELM_WIDE
L,NEWKP+2,NEWKP+3,1
! Orientation keypoint
K,,0,PAN_WIDE/2,0
! Select lines and assign them properties and orientation keypoints
LSEL, LINE, NEWLN,NEWLN+2,, ,
LATT,MAT_ALUM,R_BEAM, 2, NEWKP + 4,NEWKP + 4,1
! Mesh the lines
NUMSTR,ELEM,NEWEL
NUMSTR,NODE,NEWND
LMESH,NEWLN,NEWLN+2,,
! Now copy the elements
ESEL,S,ELEM, ,NEWEL,NEWEL+2+ELM_WIDE-1, ,
EGEN, CELL_Y,(2+ELM_WIDE)*3+1,ALL,r,r,r,r,0,PAN_WIDE,0
ESEL,S,ELEM, NEWEL,NEWEL+(2+ELM_WIDE) *CELL_Y-1, ,
EGEN, CELL_X+1,CELL_Y*((2+ELM_WIDE)*3+1),ALL, ,r,r,, ,PAN_WIDE,0,0
NEWEL = NEWEL + CELL_Y* (CELL_X+1)* (1+2*(2+ELM_WIDE))
NEWND = NEWND + CELL_Y* (CELL_X+1)* (1+2* (2+ELM_WIDE))* 2+1
NEWKP = NEWKP + 5
NEWLN = NEWLN + 3
*ENDIF! End code for making aluminum grid.
/COM *********************************
/COM **** PUT IT ALL TOGETHER ****
/COM ******************************
! Merge all the areas and keypoints and lines for everything created so far
ALLSEL,ALL,ALL
NUMMRG,NODE,PAN_TALL*.0001,
! Merge nodes
NUMMRG,NODE,PAN_TALL*.0001,
/COM ************************************
/COM ** ADD GLAST BOUNDARY CONDITIONS **
/COM ***********************************
!/COM CREATE GRAVITY, 7.0 Gee
!ACEL, 0, 9.8*7,0,
/COM NOW WE CAN FIX THE STRUCTURAL BOUNDARY CONDITIONS
! Depending on which BC is specified in the beginning of the program,
! different BC's will be applied
*IF,EIGHTUZ,EQ,TRUE,THEN
/COM **************************************************
/COM *** EIGHT POINTS SUPPORTED IN Z DIRECTION ONLY ***
/COM **************************************************
```

/COM DEFINE THE LOCATION OF THE SUPPORT POINTS
! The strategy here is to make new keypoints where we want
! BC's, assign the BC's, then merge the keypoints into the
! model.
! Constraining just one node for each support point causes point stresses ! which lead to incorrect values. Instead, we take several nodes that are ! within millimeters of each other, support one, and make the rest rigid
! with respect to the supported one. This spreads the load out slightly and
! creates a more realistic spread of stress.
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR, KP, NEWKP
K, ,PAN_WIDE, 0, 0
K, ,PAN_WIDE*3, 0, 0
K, ,PAN_WIDE,PAN_WIDE*4,0
K, , PAN_WIDE*3, PAN_WIDE*4, 0
K, 0, PAN_WIDE, 0
K, 0, PAN_WIDE*3,0
K, ,PAN_WIDE*4,PAN_WIDE, 0
K, , PAN_WIDE*4, PAN_WIDE*3, 0
! These are the keypoints at the top of the aluminum bosses
K, ,PAN_WIDE, 0,ILZ_DEEP
K, ,PAN_WIDE*3, 0, ILZ_DEEP
K, ,PAN_WIDE,PAN_WIDE*4,ILZ_DEEP
K, ,PAN_WIDE*3,PAN_WIDE*4, ILZ_DEEP
K, , 0, PAN_WIDE, ILZ_DEEP
K, , 0, PAN_WIDE*3, ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE,ILZ_DEEP
K, ,PAN_WIDE*4, PAN_WIDE*3, ILZ_DEEP
! These are the keypoints at the inside of the aluminum bosses
K, , PAN_WIDE, PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*3, PAN_THCK/2, ILZ_DEEP
K, ,PAN_WIDE,PAN_WIDE*4-PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*3,PAN_WIDE*4-PAN_THCK/2,ILZ_DEEP
K, ,PAN_THCK/2,PAN_WIDE,ILZ_DEEP
K, , PAN_THCK/2, PAN_WIDE*3, ILZ_DEEP
K, ,PAN_WIDE*4-PAN_THCK/2,PAN_WIDE,ILZ_DEEP
K, ,PAN_WIDE*4-PAN_THCK/2,PAN_WIDE*3,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, , PAN_WIDE+PAN_THCK/2,0,ILZ_DEEP
K, ,PAN_WIDE*3+PAN_THCK/2, 0, ILZ_DEEP
K, ,PAN_WIDE+PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP
K, ,PAN_WIDE*3+PAN_THCK/2,PAN_WIDE*4, ILZ_DEEP
K, 0, PAN_WIDE+PAN_THCK/2,ILZ_DEEP
K, 0, PAN_WIDE*3+PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4, PAN_WIDE+PAN_THCK/2, ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE*3+PAN_THCK/2, ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE-PAN_THCK/2,0,ILZ_DEEP
K, ,PAN_WIDE*3-PAN_THCK/2, 0, ILZ_DEEP
K, ,PAN_WIDE-PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP

```
K, ,PAN_WIDE*3-PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP
K, ,O,PAN_WIDE-PAN_THCK/2,ILZ_DEEP
K,,0,PAN_WIDE*3-PAN_THCK/2,ILZ_DEEP
K,,PAN_WIDE*4,PAN_WIDE-PAN_THCK/2,ILZ_DEEP
K,,PAN_WIDE*4,PAN_WIDE*3-PAN_THCK/2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE+PAN_THCK/2,0,0
K,,PAN_WIDE*3+PAN_THCK/2,0,0
K,,PAN_WIDE+PAN_THCK/2,PAN_WIDE*4,0
K, ,PAN_WIDE*3+PAN_THCK/2,PAN_WIDE*4,0
K, ,0,PAN_WIDE+PAN_THCK/2,0
K, ,0,PAN_WIDE*3+PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE+PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE*3+PAN_THCK/2,0
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE-PAN_THCK/2,0,0
K,,PAN_WIDE*3-PAN_THCK/2,0,0
K,,PAN_WIDE-PAN_THCK/2,PAN_WIDE*4,0
K,,PAN_WIDE*3-PAN_THCK/2,PAN_WIDE*4,0
K, ,0,PAN_WIDE-PAN_THCK/2,0
K, 0,PAN_WIDE*3-PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE-PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE*3-PAN_THCK/2,0
! Now make new nodes at all these keypoints so we can use the
! CERIG command to make them rigid
! Start numbering them at some huge number
NUMCMP,NODE
NUMSTR,NODE,NEWND
KSEL,,,,NEWKP,NEWKP+55 ! Select the keypoints we just made
NKPT,,ALL! Create nodes at all selected keypoints
! Now rigidly attach the top to the bottom and inside of the boss nodes
*DO,N,0,7
CERIG,NEWND+N,NEWND+8+N,ALL
CERIG,NEWND+N,NEWND+16+N,ALL
CERIG,NEWND+N,NEWND+24+N,ALL
CERIG,NEWND+N,NEWND+32+N,ALL
CERIG,NEWND+N,NEWND+40+N,ALL
CERIG,NEWND+N,NEWND+48+N,ALL
*ENDDO
! Select the keypoints at the bottom
KSEL, S,KP, ,NEWKP,NEWKP+7
! This is the BC where all 8 are only constrained in the "Y" direction
DK,ALL, ,0, ,1,UZ,,, , , ,
! Merge nodes so the old nodes take on the properties we've assigned to
! the new ones that overlap them
NUMMERG,NODE,PAN_TALL*.0001, , ,HIGH
! Select all the keypoints again so we can merge the BC KPs
ALLSEL,ALL,KP
! Merge keypoints
NUMMERG,KP,PAN_TALL*.0001
! Select everything so it's there for the solution
ALLSEL,ALL,ALL
```

```
*ENDIF ! End 8 node UZ support
*IF,FOURUZ,EQ,TRUE,THEN
/COM **************************************************
/COM *** FOUR POINTS SUPPORTED IN Z DIRECTION ONLY ***
/COM **************************************************
/COM DEFINE THE LOCATION OF THE SUPPORT POINTS
! The strategy here is to make new keypoints where we want
! BC's, assign the BC's, then merge the keypoints into the
! model. More flexible than having to know which KPs
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR,KP,NEWKP
K,,PAN_WIDE*2,0,0
K,,PAN_WIDE*2,PAN_WIDE*4,0
K,,0,PAN_WIDE*2,0
K,,PAN_WIDE*4,PAN_WIDE*2,0
! These are the keypoints at the top of the aluminum bosses
K,,PAN_WIDE*2,0,ILZ_DEEP
K,,PAN_WIDE*2,PAN_WIDE*4,ILZ_DEEP
K, 0,PAN_WIDE*2,ILZ_DEEP
K,,PAN_WIDE*4,PAN_WIDE*2,ILZ_DEEP
! These are the keypoints at the inside of the aluminum bosses
K,,PAN_WIDE*2,PAN_THCK/2,ILZ_DEEP
K,,PAN_WIDE*2,PAN_WIDE*4-PAN_THCK/2,ILZ_DEEP
K,,PAN_THCK/2,PAN_WIDE*2,ILZ_DEEP
K,,PAN_WIDE*4-PAN_THCK/2,PAN_WIDE*2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE*2+PAN_THCK/2,0,ILZ_DEEP
K,,PAN_WIDE*2+PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP
K,,0,PAN_WIDE*2+PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE*2+PAN_THCK/2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K,,PAN_WIDE*2-PAN_THCK/2,0,ILZ_DEEP
K,,PAN_WIDE*2-PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP
K,,0,PAN_WIDE*2-PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE*2-PAN_THCK/2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K,,PAN_WIDE*2+PAN_THCK/2,0,0
K,,PAN_WIDE*2+PAN_THCK/2,PAN_WIDE*4,0
K,,0,PAN_WIDE*2+PAN_THCK/2,0
K, ,PAN_WIDE*4,PAN_WIDE*2+PAN_THCK/2,0
! These are the keypoints at the edges of the interlace nodes
K,,PAN_WIDE*2-PAN_THCK/2,0,0
K,,PAN_WIDE*2-PAN_THCK/2,PAN_WIDE*4,0
K,,0,PAN_WIDE*2-PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE*2-PAN_THCK/2,0
```

! Now make new nodes at all these keypoints so we can use the CERIG command

```
! Start numbering them at some huge number
NUMCMP,NODE
NUMSTR,NODE,NEWND
KSEL,,,,NEWKP,NEWKP+27 ! Select the keypoints we just made
NKPT,,ALL ! Create nodes at all selected keypoints
! Now rigidly attach the top to the bottom and inside of the boss nodes
*DO,N,0,3
CERIG,NEWND+N,NEWND+4+N,ALL
CERIG,NEWND+N,NEWND+8+N,ALL
CERIG,NEWND+N,NEWND+12+N,ALL
CERIG,NEWND+N,NEWND+16+N,ALL
CERIG,NEWND+N,NEWND+20+N,ALL
CERIG,NEWND+N,NEWND+24+N,ALL
*ENDDO
! Select the keypoints at the bottom
KSEL,S,KP, ,NEWKP,NEWKP+3
! This is the BC where all 8 are only constrained in Y
DK,ALL, ,0, ,1,UZ,,, , , ,
! Merge nodes
NUMMERG,NODE,PAN_TALL*.0001, , ,HIGH
! Select all the keypoints again so we can merge the BC KPs
ALLSEL,ALL, KP
! Merge keypoints
NUMMERG,KP,PAN_TALL*.0001
! Select everything so it's there for the solution
ALLSEL,ALL, ALL
*ENDIF! End 4 node UZ support
/COM ************************************************************
/COM *** A PROGRAM FOR SAVING THE RESULTS OF A MODAL ANALYSIS ***
/COM ******************************************************************
! 12/11/00
/COM This one does 6 layer walls
! This section loops through a variety of layup possibilities for
! both the wall and core. This program is tailored to walls that
! are six layers thick, but can be easily modified by altering the
! section below where the real constants are redefined.
```


## /PREP 7

## /COM CREATE A DIMENSIONED ARRAY OF ANGLES

! These values will serve as lookups for the different possible angles
! of plies in a layup
*DIM, WALLNGL, ARRAY, 8
*DIM, CORENGL, ARRAY, 9
*DIM, WALLNM, CHAR, 8
*DIM, CORENM, CHAR, 9
! And some numbers
*DIM, NUMS, CHAR, 8
*SET, NUMS (1),'000','001','002','003','004','005','006','007'
! In the following assignments there is a code

```
! 900 = 0/90's
! 104 = 0/45/-45/90's
! 103 = 0/60/-60's
*SET,WALLNGL (1),0,15, 30,45,60,75,90,900
*SET, CORENGL (1),0,15,30,45,60,75,90,900
*SET,CORENGL(9),104
*SET,WALLNM(1),'0','15','30','45','60','75','90','0_90'
*SET,CORENM(1),'0','15','30','45','60','75','90','0_90'
*SET,CORENM(9),'quasi'
/COM LOOP THROUGH ALL DESIGNS
*DO,WALL,1,8
*DO,CORE,1,9
! These loop through the angle ply, 0/90, and quasiisotropic
! options
```

/COM DEAL WITH THE WALLS
*IF, WALLNGL (WALL) , EQ, 900, THEN
/COM WALL IS 0/90s
! If the walls are 0/90's then modify the non-interlaced elements
RMODIF,1,13,MAT_T300,0,PLY_THCK,
RMODIF,1,16,MAT_T300,0,PLY_THCK,
RMODIF,1,19,MAT_T300,90,PLY_THCK,
RMODIF,1,22,MAT_T300,90,PLY_THCK,
RMODIF,1,25,MAT_T300,0,PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
RMODIF,1,67,MAT_T300,0,PLY_THCK,
RMODIF, 1, 70, MAT_T300,0,PLY_THCK,
RMODIF,1,73,MAT_T300,90,PLY_THCK,
RMODIF,1,76,MAT_T300,90,PLY_THCK,
RMODIF,1,79,MAT_T300,0,PLY_THCK,
RMODIF, 1, 82, MAT_T300,0,PLY_THCK,
! and modify the interlaced elements
RMODIF, 2, 13, MAT_T300,0,PLY_THCK,
RMODIF,2,16, MAT_T300,0,PLY_THCK,
RMODIF, 2, 19, MAT_T300,90, PLY_THCK,
RMODIF, 2, 22,MAT_T300,90,PLY_THCK,
RMODIF, 2, 25, MAT_T300,0,PLY_THCK,
RMODIF, 2, 28, MAT_T300,0,PLY_THCK,
RMODIF, 2, 34, MAT_T300,0, PLY_THCK,
RMODIF, 2, 37, MAT_T300,0, PLY_THCK,
RMODIF, 2, 40,MAT_T300,90,PLY_THCK,
RMODIF, 2, 43, MAT_T300,90,PLY_THCK,
RMODIF, 2, 46, MAT_T300,0, PLY_THCK,
RMODIF, 2, 49, MAT_T300,0,PLY_THCK,
*ELSEIF,WALLNGL (WALL) ,EQ, 103, THEN
/COM WALL IS 0/60/-60s
! If the walls are 0/90's then modify the non-interlaced elements
RMODIF, 1, 13, MAT_T300,0, PLY_THCK,
RMODIF,1,16,MAT_T300,60,PLY_THCK,
RMODIF,1,19,MAT_T300,-60,PLY_THCK,
RMODIF,1,22,MAT_T300,-60,PLY_THCK,

RMODIF,1,25,MAT_T300,60,PLY_THCK, RMODIF,1,28,MAT_T300,0,PLY_THCK,

RMODIF,1,67,MAT_T300,0,PLY_THCK, RMODIF, 1, 70, MAT_T300,60,PLY_THCK, RMODIF,1,73,MAT_T300,-60,PLY_THCK, RMODIF, 1,76, MAT_T300,-60,PLY_THCK, RMODIF,1,79,MAT_T300,60,PLY_THCK, RMODIF,1,82,MAT_T300,0,PLY_THCK,
! and modify the interlaced elements RMODIF, 2, 13, MAT_T300,0,PLY_THCK, RMODIF, 2, 16, MAT_T300,60,PLY_THCK, RMODIF, 2, 19, MAT_T300,-60,PLY_THCK, RMODIF, 2, 22, MAT_T300,-60,PLY_THCK, RMODIF, 2, 25, MAT_T300,60, PLY_THCK, RMODIF, 2, 28, MAT_T300,0,PLY_THCK,

RMODIF, 2, 34, MAT_T300,0,PLY_THCK, RMODIF, 2, 37, MAT_T300,60,PLY_THCK, RMODIF, 2, 40, MAT_T300,-60, PLY_THCK, RMODIF, 2, 43, MAT_T300,-60, PLY_THCK, RMODIF, 2, 46, MAT_T300,60,PLY_THCK, RMODIF, 2, 49, MAT_T300,0,PLY_THCK,

```
*ELSE ! Else we use just the angles
```

/COM WALL IS ANGLES
WALLNGL1 $=$ WALLNGL (WALL)
WALLNGL2 $=-$ WALLNGL1
RMODIF, 1, 13, MAT_T300,0,PLY_THCK,
RMODIF,1,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,19,MAT_T300,WALLNGL1, PLY_THCK,
RMODIF,1,22,MAT_T300,WALLNGL1, PLY_THCK,
RMODIF,1,25,MAT_T300,WALLNGL2, PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
RMODIF, 1, 67, MAT_T300,0, PLY_THCK,
RMODIF,1,70,MAT_T300,WALLNGL2, PLY_THCK,
RMODIF,1,73,MAT_T300,WALLNGL1, PLY_THCK,
RMODIF,1,76,MAT_T300,WALLNGL1, PLY_THCK,
RMODIF,1,79,MAT_T300,WALLNGL2, PLY_THCK,
RMODIF,1,82,MAT_T300,0,PLY_THCK,
! and modify the interlaced elements
RMODIF, 2, 13, MAT_T300, 0, PLY_THCK,
RMODIF, 2, 16, MAT_T300,WALLNGL2, PLY_THCK,
RMODIF, 2, 19, MAT_T300,WALLNGL1, PLY_THCK,
RMODIF, 2, 22, MAT_T300,WALLNGL1, PLY_THCK,
RMODIF,2,25,MAT_T300,WALLNGL2, PLY_THCK,
RMODIF, 2, 28, MAT_T 300,0, PLY_THCK,
RMODIF, 2, 34, MAT_T300,0,PLY_THCK,
RMODIF, 2, 37, MAT_T300,WALLNGL2, PLY_THCK,
RMODIF, 2, 40, MAT_T300,WALLNGL1, PLY_THCK,
RMODIF, 2, 43, MAT_T300,WALLNGL1, PLY_THCK,
RMODIF, 2, 46, MAT_T300,WALLNGL2, PLY_THCK,
RMODIF, 2, 49, MAT_T300,0,PLY_THCK,
*ENDIF ! Wall

```
/COM NOW DEAL WITH CORE
*IF, CORENGL (CORE),EQ,900,THEN
! If it's 0/90 layup
/COM CORE IS 0/90
CORENGL1 = 90
CORENGL2 = 0
```

RMODIF,1,31,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,34,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,37,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,40,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,43,MAT_T300,CORENGL1, PLY_THCK,
RMODIF,1,46,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,49,MAT_T300,CORENGL2,PLY_THCK,
RMODIF, 1,52,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,55,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,58,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,61,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,64,MAT_T300,CORENGL1,PLY_THCK,
*ELSEIF, CORENGL (CORE) ,EQ, 103
/COM CORE IS QUASI
! If it's quasiisotropic with 0/60/-60
RMODIF, 1, 31, MAT_T300,0, PLY_THCK,
RMODIF, 1, 34, MAT_T300,60,PLY_THCK,
RMODIF,1,37,MAT_T300,-60,PLY_THCK,
RMODIF,1,40,MAT_T300,-60,PLY_THCK,
RMODIF,1,43, MAT_T300,60,PLY_THCK,
RMODIF,1,46,MAT_T300,0,PLY_THCK,
RMODIF,1,49,MAT_T300,0,PLY_THCK,
RMODIF,1,52,MAT_T300,60,PLY_THCK,
RMODIF,1,55,MAT_T300,-60,PLY_THCK,
RMODIF,1,58, MAT_T300,-60,PLY_THCK,
RMODIF, 1, 61, MAT_T300,60,PLY_THCK,
RMODIF, 1, 64, MAT_T300,0,PLY_THCK,
*ELSE ! Else we use just the angles
/COM CORE IS ANGLES
CORENGL1 $=$ CORENGL (CORE)
CORENGL2 $=-$ CORENGL1
RMODIF,1,31, MAT_T300, CORENGL1,PLY_THCK,
RMODIF,1,34,MAT_T300, CORENGL2,PLY_THCK,
RMODIF,1,37,MAT_T300, CORENGL1, PLY_THCK,
RMODIF,1,40,MAT_T300, CORENGL2,PLY_THCK,
RMODIF,1,43,MAT_T300,CORENGL1, PLY_THCK,
RMODIF,1,46,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,49,MAT_T300,CORENGL2, PLY_THCK,
RMODIF,1,52,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,55, MAT_T300, CORENGL2, PLY_THCK,
RMODIF,1,58,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,61,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,64, MAT_T300,CORENGL1,PLY_THCK,

```
*ENDIF ! Core
/COM NOW WE GO AHEAD AND SOLVE IT AGAIN
/ SOLU
/COM SET UP A MODAL ANALYSIS
! This next section uses powerdynamics and look for NUM_MODES modes,
! three of which are defined as rigid body modes. The rigid body modes
! account for the fact that we don't have any constraints besides translation
! in one direction. Doing it this way allows us to see modes which might
! otherwise be eliminated in the model but still exist in the real grid
ANTYPE,2
!*
MODOPT,SUBSP,8
EQSLV,PCG
MXPAND,8, , ,0
LUMPM,0
PSTRES,0
!*
MODOPT,SUBSP,8,0,0, ,OFF
RIGID,UX,UY,ROTZ
SUBOPT,0,0, ,100,
!*
/COM RUN THE SOLUTION - go get some coffee, read a book
SOLVE
/COM NOW THAT IT'S SOLVED, RECORD RESULTS
! This section prints out the modes to graphics files, and labels them
! so they can be viewed later
/POST1
/COM CYCLE THROUGH THE FIRST 4 MODES
! First define graphics output variables
JPEG, QUAL, 75,
JPEG,ORIENT,HORIZ
JPEG,COLOR,2
JPEG,TMOD,1
/GFILE,600,
*DO,MODE,1,5
/TITLE,W%WALLNM (WALL) %C%CORENM (CORE) %M%NUMS (MODE+3)%
SET,,, ,,, ,MODE+2
PLDISP,0
/SHOW,JPEG
*ENDDO ! graphics loop
*DO,MODE,1,5
/RENAME,file%NUMS (MODE) %, jpg, ,W%WALLNM(WALL) %C%CORENM(CORE) %M%NUMS (MODE+3) %,jpg
,
*ENDDO ! rename loop
/DELETE,file005,jpg,..\
FINISH
/PREP7
```

| *ENDDO |  |
| :--- | :--- |
| *ENDDO |  |
| /eof | ! wall loop |

## A. 2 FAILURE ANALYSIS PROGRAM

```
/COM,ANSYS RELEASE 5.6 UP19991022 19:29:20 04/12/2000
/PREP7
/COM A GLAST MODEL THAT INCLUDES SLOTS AND LAMINATES
! 11/28/00 - Michael Hicks
! This program accepts a number of variable inputs that define
! a composite grid made using the slotted TRIG technique. For
! GLAST the program has the option to include the stiffness of
! an aluminum heat pipe grid and the bottom tray of the tracker
! towers.
! After assembling the model, it can be made to examine different
! possible layup options and returning the first ply failure
! strength ratio for the laminates involved.
! All units are SI: meters, kilograms, pascals, etc.
! Note that ilz is often used as an abbreviation for interlace
! Define Boolean variables
TRUE = 1
FALSE = 0
/COM DEFINE THE MODEL
! Grid parameters
CELL_X=4 ! Number of grid cells in the x direction
CELL_Y=4 ! Number of grid cells in the y direction
INCLGRID=TRUE ! Include the aluminum grid or not
INCLTPPN=TRUE ! Include the top panel or not
MASSES=TRUE ! Include the tower and cal masses or not
! Boundary conditions
EIGHTUZ=TRUE ! Use 8 points free in all but z direction
FOURUZ=FALSE ! Use 4 mid-side points free in all but z direction
! Meshing
ELM_WIDE=4 ! Number of elements across the main section of the panel
ILZ_TALL=2 ! Number of elements up the ilz sections
NLZ_TALL=4 ! Number of elements up the nilz sections
! Geometry
PAN_WIDE=.372 ! Panel width
PAN_TALL=.24 ! Panel height
ILZ_DEEP=.03 ! Interlace height
! Layup
! A cross-section of the panel (a rib of the grid)
! on its side would look like:
! +-----------------------------------------------------------
```



```
PLY_THCK=.00025 ! Cured ply thickness
NUM_PLYS=24 ! Number of plies through the entire panel thickness
WLL_PLYS=6 ! Number of plies in a wall (panel is wall:ilz:wall)
CORENGL1=45 ! Angle for one of two alternating layers for the core section
CORENGL2=-45! Angle for one of two alternating layers for the core section
WALLNGL1=45 ! Angle for one of two alternating layers for the wall section
WALLNGL2=-45! Angle for one of two alternating layers for the wall section
! Top aluminum flange (included if INCLGRID = TRUE)
TOP_WIDE=.0254 ! Top flange width
TOP_TALL=.0204 ! Top flange height - 25.4 mm minus 5 mm to approx
    ! hollow heat pipe
! Additional calculated geometry
PAN_THCK=NUM_PLYS*PLY_THCK ! Panel thickness
MN_WIDE=PAN_WIDE-PAN_THCK ! Width of main meshing area
```

```
/COM REAL CONSTANTS DEFINED
! Make real constants for masses (kg)
CAL_MASS=102.6
    ! Calorimeter mass
TOW_MASS=32.6 ! Tower mass
TPEMASS=TOW_MASS/((ELM_WIDE*2+1)*4) ! Top edge mass
BTCRMASS=CAL_MASS/8 ! 1/8th of the calorimeter mass
```

```
/COM MATERIALS DEFINED
! Make Material 1 as Aluminum
UIMP,1,EX, , ,76E9,
UIMP,1,KXX, , , 240,
! YS90A/25C prepreg
UIMP,3,EX,EY,EZ,520E9,5.7E9,5.7E9,
UIMP, 3, PRXY,PRYZ,PRXZ,.3,.3,.3,
UIMP, 3,NUXY,NUYZ,NUXZ, , , ,
UIMP, 3, GXY,GYZ, GXZ,5.1E9,3.195E9,3.195E9,
UIMP, 3, ALPX, ALPY, ALP Z,14.78E-6,14.78E-6,22.5E-6,
UIMP,3,DENS, , ,1750,
! Create failure criteria for YS90 prepreg
TB,FAIL,3,1 ! For material 3 with only 1 temperature
TBTEMP,,CRIT ! The next values are a failure criterion
TBDATA,1,0,0,2 ! Use Tsai-Wu failure criterion
TBTEMP,0 ! At standard 0 temperature
TBDATA,10,1860E6 ! Max X Tensile Strength
TBDATA,11,-350E6 ! Max X Compressive Strength
TBDATA,12,33E6 ! Max Y Tensile Strength
TBDATA,13,-256E6 ! Max Y Compressive Strength
TBDATA,14,33E6 ! Max Z Tensile Strength
TBDATA,15,-256E6 ! Max Z Compressive Strength
TBDATA,16,59E6 ! Max XY shear
```

```
TBDATA,17,59E6 ! Max YZ shear (although I have no data for it)
TBDATA,18,59E6 ! Max ZX shear
TBDATA,19,-1 ! XY coupling constant
TBDATA,20,-1 ! YZ coupling constant
TBDATA,21,-1 ! ZX coupling constant
! YS90A interlace .4 vf (Externally calculated)
UIMP,4,EX,EY,EZ,354.1E9,5.1641E9,5.1641E9,
UIMP,4,PRXY,PRYZ,PRXZ,.496,.3,.3,
UIMP,4,NUXY,NUYZ,NUXZ, ,,,
UIMP,4,GXY,GYZ,GXZ,2.89E9,1.37E9,2.89E9,
UIMP,4,ALPX,ALPY,ALPZ,-1.129E-6,60E-6,60E-6,
UIMP,4,DENS, , ,2060,
! Core material in Towers - aluminum honeycomb
UIMP,5,EX,EY,EZ,2.7E9,2.7E9,2.7E9,
UIMP,5,PRXY,PRYZ,PRXZ,.3,.3,.3,
UIMP,5,NUXY,NUYZ,NUXZ, , , ,
UIMP,5,GXY,GYZ,GXZ, 2.62E3,3.26E9,1.9E9,
UIMP,5,ALPX,ALPY,ALPZ,.02E-6,22.5E-6,22.5E-6,
UIMP,5,DENS, , ,16,
! Give names to the material numbers so it's easier to see
! what I'm doing
MAT_ALUM=1
MAT_TPAN=2
MAT_T300=3 ! This is actually YS90 but I didn't bother changing
    ! the names through all the following sections
MAT_ILZ=4
MAT_CORE=5
/COM CREATE ELEMENTS
! Create mass element
ET,1,MASS21
! Make it not have a rotational inertia
KEYOPT,1,2,0
KEYOPT,1,3,2
! Create 3 node beam element
ET,2,BEAM189
! Create linear-layered shell element
! Specify that stress will be used, all failure stuff recorded,
! all plies, and strains evaluated at top and bottom.
! ET,3,SHELL99,,,,,2,5,,,
ET,3,SHELL99,,0,4,0,2,5
KEYOPT,3,8,1
/COM CREATE REAL CONSTANTS DESCRIBING LAMINATES
! Non-interlaced (Nilz) section of the panel real constant
R_NILZ = 1
R,1
RMODIF,1,1,NUM_PLYS,0,0,0,0,0
! Each of these is a layer defined by material, angle, thickness
RMODIF,1,13,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,19,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,22,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,25,MAT_T300,0,PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
```

```
!
RMODIF,1,31,MAT_T300,45,PLY_THCK,
RMODIF,1,34,MAT_T300,-45,PLY_THCK,
RMODIF,1,37,MAT_T300,45,PLY_THCK,
RMODIF,1,40,MAT_T300,-45,PLY_THCK,
RMODIF,1,43,MAT_T300,90,PLY_THCK,
RMODIF,1,46,MAT_T300,90,PLY_THCK,
RMODIF,1,49,MAT_T300,90,PLY_THCK,
RMODIF,1,52,MAT_T300,90,PLY_THCK,
RMODIF,1,55,MAT_T300,-45,PLY_THCK,
RMODIF,1,58,MAT_T300,45,PLY_THCK,
RMODIF,1,61,MAT_T300,-45,PLY_THCK,
RMODIF,1,64,MAT_T300,45,PLY_THCK,
!
RMODIF,1,67,MAT_T300,0,PLY_THCK,
RMODIF,1,70,MAT_T300,0,PLY_THCK,
RMODIF,1,73,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,76,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,79,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,82,MAT_T300,WALLNGL1,PLY_THCK,
! Interlaced (Ilz) section of the panel real constants
R_ILZ=2
R,2
RMODIF,2,1,2*WLL_PLYS+1,0,0,0,0,0
! Each of these is a layer defined by material, angle, thickness
RMODIF,2,13,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,19,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,22,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,25,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,28,MAT_T300,WALLNGL1,PLY_THCK,
!
RMODIF,2,31,MAT_ILZ,0,(NUM_PLYS-2*WLL_PLYS)*PLY_THCK,
!
RMODIF,2,34,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,37,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,40,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,43,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,46,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,49,MAT_T300,WALLNGL1,PLY_THCK,
! Interlace-only (no enclosing walls) real contants
R_ILZN=3
R,3
RMODIF,3,1,1,0,0,0,0,0
RMODIF,3,13,MAT_ILZ,0,(NUM_PLYS-2*WLL_PLYS)*PLY_THCK,
! Tower bottom panels. These are honeycomb core sandwiches
R_TOW=4
R,4
! Each of these is a layer defined by material, angle, thickness
RMODIF,4,1,13,0,0,0,0,0
RMODIF,4,13,MAT_T300,0,.000225/6,
RMODIF,4,16,MAT_T300,60,.000225/6,
RMODIF,4,19,MAT_T300,-60,.000225/6,
RMODIF,4,22,MAT_T300,-60,.000225/6,
```

```
RMODIF,4,25,MAT_T300,60,.000225/6,
RMODIF,4,28,MAT_T300,0,.000225/6,
!
RMODIF,4,31,MAT_CORE,0,.034-2*.000225,
!
RMODIF,4,34,MAT_T300,0,.000225/6,
RMODIF,4,37,MAT_T300,60,.000225/6,
RMODIF,4,40,MAT_T300,-60,.000225/6,
RMODIF,4,43,MAT_T300,-60,.000225/6,
RMODIF,4,46,MAT_T300,60,.000225/6,
RMODIF,4,49,MAT_T300,0,.000225/6,
! Mass element real constants
R_CAL=5
R,5,BTCRMASS
R_TOWER=6
R,6,TPEMASS
R_BEAM=7
R,7, , , , ,
! Beam Cross-section
SECTYPE, 1, BEAM, RECT, topflange
SECOFFSET, USER, 0, TOP_WIDE/2
SECDATA,TOP_TALL,TOP_WIDE,0,0,0,0,0,0,0,0
/COM ESTABLISH LABELS TO KEEP TRACK OF NUMBERS
! Note that I later found that ANSYS has an automatic way of doing this
NEWKP = 1 ! New keypoint
NEWND = 1 ! New node
NEWLN = 1 ! New line
NEWAR = 1 ! New area
NEWEL = 1 ! New element
NEWND = 1 ! New node
/COM ***************************************
/COM **** MAKE GRID BY CELL WALL PANELS ****
/COM ***************************************
! This section produces a group of meshed areas representing a single
! panel as diagrammed below
! interlace only -> | | | walls and interlace |
! By copying and connecting the areas we create any entire rib
! which is then copied to produce the composite grid
/COM ESTABLISH KEYPOINTS
NUMSTR,KP,NEWKP
```

```
! This is the bottom row
K, ,0,0,0
K,,PAN_THCK/2,0,0
K,,PAN_WIDE-PAN_THCK/2,0,0
K,,PAN_WIDE,0,0
NUMSTR,LINE,NEWLN
! Make lines along the bottom row.
L, NEWKP,NEWKP+1,1
L,NEWKP+1,NEWKP+2,ELM_WIDE
L,NEWKP+2,NEWKP+3,1
! Copy this row up three times to get horizontal lines for one panel,
LGEN, 2,NEWLN,NEWLN+2,1,0,0,ILZ_DEEP
LGEN, 2,NEWLN,NEWLN+2,1,0,0,PAN_TALL/2
LGEN, 2,NEWLN,NEWLN+2,1,0,0,PAN_TALL-ILZ_DEEP
LGEN, 2,NEWLN,NEWLN+2,1,0,0,PAN_TALL
KP1 = NEWKP ! Remember what the first keypoint was
NEWKP = NEWKP + 20 ! New new keypoint
! This is the vertical column of KP's
NUMSTR,KP,NEWKP
K, ,0,0,ILZ_DEEP
K,,0,0,PAN_TALL/2
K,,0,0,PAN_TALL-ILZ_DEEP
K, ,0,0,PAN_TALL
! Make lines along side
L,KP1,NEWKP,ILZ_TALL
L,NEWKP,NEWKP+1,NLZ_TALL/2
L,NEWKP+1,NEWKP+2,NLZ_TALL/2
L,NEWKP+2,NEWKP+3,ILZ_TALL
! Copy this column sideways three times to get vertical lines for one panel,
LGEN, 2,NEWLN+15,NEWLIN+19,1,PAN_THCK/2,0,0
LGEN, 2,NEWLN+15,NEWLIN+19,1,PAN_WIDE-PAN_THCK/2,0,0
LGEN, 2,NEWLN+15,NEWLIN+19,1,PAN_WIDE,0,0
! Merge keypoints
NUMMRG,KP,
NEWKP = KP1 + 20
! Move the keypoints a little near the point where the ribs contact
! in the middle of the slots so that the nodes created there
! will not overlap. Move them 1/1000th of the panel height.
KMODIF,KP1+8,0,0,PAN_TALL/2+PAN_TALL*.001
KMODIF,KP1+11,PAN_WIDE,0,PAN_TALL/2+PAN_TALL*.001
! Now make the areas that will have only interlace and
! assign the proper elements, etc to them.
NUMSTR,AREA,NEWAR
AL,NEWLN,NEWLN+19,NEWLN+3,NEWLN+15
AL,NEWLN+2,NEWLN+27,NEWLN+5,NEWLN+23
AL,NEWLN+9,NEWLN+22,NEWLN+12,NEWLN+18
AL,NEWLN+11,NEWLN+30,NEWLN+14,NEWLN+26
```

```
ASEL, S,AREA, NEWAR,NEWAR+3
AATT,MAT_ILZ,R_ILZ,3,
! Temporarily use ilz rather than ilzn
! Then the areas that will have interlace and walls.
AL,NEWLN+1,NEWLN+23,NEWLN+4,NEWLN+19
AL,NEWLN+10,NEWLN+26,NEWLN+13,NEWLN+22
ASEL,S,AREA, ,NEWAR+4,NEWAR+5
AATT,MAT_ILZ,R_ILZ,3,0
! Then the non-interlaced areas
AL, NEWLN+4,NEWLN+24,NEWLN+7,NEWLN+20
AL,NEWLN+7,NEWLN+25,NEWLN+10,NEWLN+21
AL,NEWLN+6,NEWLN+21,NEWLN+9,NEWLN+17
AL,NEWLN+8,NEWLN+29,NEWLN+11,NEWLN+25
ASEL,S,AREA, ,NEWAR+6,NEWAR+9
AATT,MAT_NILZ,R_NILZ,3,
! Cut out the lines where the slots are
LDELE,NEWLN+16,
LDELE,NEWLN+28,
! Compress line numbers and figure out what the next NEWLN should be
NUMCMP,LINE
/COM COPY WALL TO PRODUCE OPPOSITE WALL OF CELL
ALLSEL,ALL, ALL
! For some strange reason I have to subtract 1 from the number
! I would have put on the itimes value in the x copy command
AGEN, 2,NEWAR,NEWAR+9,,0,PAN_WIDE,0
/COM NOW DUPLICATE THESE TO FORM Y DIRECTION WALLS
! This is accomplished by spinning them around the xy axis so
! the slots wind up in the right place
! move the work-plane from the bottom up to the top of the grid
wpof,,,PAN_TALL
! rotate it }180\mathrm{ about the x axis then -90 about the z axis
wpro,0,180,0
wpro,-90,0,0
! create coordinate system number }11\mathrm{ on the workplane
! CSWPLA,11,0,1,1
! make the workplane the active system
CSYS,4
! now make a copy of all areas from the new coordinate system to global (0)
ALLSEL,ALL, ALL
ATRAN, 0,ALL, , , 0,0
! Put the workplane back to the global coords and make it current
WPCSYS,-1,0
CSYS,0
! Merge keypoints, making sure that the keypoints in the middle of the slot
! are not merged.
! NUMMRG,ALL,PAN_TALL*.0001,
! Update the other NEW things
NEWAR = NEWAR+40
NEWKP = KP1 + 80
NEWLN = NEWLN + 120
```

```
*IF,INCLTPPN,EQ,TRUE,THEN ! If we want top panels, execute this code.
/COM *************************************************************
/COM **** IF THE TOWER PANELS (OR A SKIN) IS TO BE INCLUDED ****
/COM ***********************************************************
/COM NOW ADD THE TOP PANEL (BOTTOM PANEL OF THE TOWER).
! Assign new keypoints from the right number
NUMSTR,KP,NEWKP
K, ,0,0,PAN_TALL
K,,PAN_THCK/2,0,PAN_TALL
K, ,PAN_WIDE-PAN_THCK/2,0,PAN_TALL
K,,PAN_WIDE,0,PAN_TALL
K, ,0,PAN_THCK/2,PAN_TALL
K,,PAN_THCK/2,PAN_THCK/2,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,PAN_THCK/2,PAN_TALL
K,,PAN_WIDE,PAN_THCK/2,PAN_TALL
K,,0,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,PAN_THCK/2,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,PAN_WIDE-PAN_THCK/2,PAN_TALL
K,,PAN_WIDE,PAN_WIDE-PAN_THCK/2,PAN_TALL
K, ,0,PAN_WIDE,PAN_TALL
K,,PAN_THCK/2,PAN_WIDE,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,PAN_WIDE,PAN_TALL
K,,PAN_WIDE,PAN_WIDE,PAN_TALL
! Make the lines starting at the right number
NUMSTR,LINE,NEWLN
L,NEWKP+1,NEWKP + 2,ELM_WIDE
L,NEWKP+2,NEWKP + 6,1
L,NEWKP+6,NEWKP +5,ELM_WIDE
L, NEWKP+5,NEWKP +1,1
L,NEWKP+4,NEWKP +5,1
L,NEWKP+5,NEWKP+9,ELM_WIDE
L, NEWKP+9,NEWKP+8,1
L,NEWKP+8,NEWKP+4,ELM_WIDE
L, NEWKP+6,NEWKP + 7,1
L, NEWKP + 7, NEWKP +11,ELM_WIDE
L,NEWKP+11,NEWKP+10,1
L,NEWKP+10,NEWKP+6,ELM_WIDE
L,NEWKP+9,NEWKP+10,ELM_WIDE
L,NEWKP+10,NEWKP+14,1
L,NEWKP+14,NEWKP+13,ELM_WIDE
L, NEWKP+13,NEWKP + 9,1
! Now make the areas
NUMSTR,AREA,NEWAR
AL,NEWLN, NEWLN+1,NEWLN+2,NEWLN+3
AL, NEWLN+4,NEWLN+5,NEWLN+6,NEWLN+7
AL,NEWLN+8,NEWLN+9,NEWLN+10,NEWLN+11
AL,NEWLN+12,NEWLN+13,NEWLN+14,NEWLN+15
```

```
AL,NEWLN+2,NEWLN+5,NEWLN+11,NEWLN+12
```

! Specify elements for panels
ASEL, S, AREA, , NEWAR, NEWAR+4
AATT, MAT_CORE, R_TOW, 3,
*ENDIF ! End of top panel code
NEWKP = NEWKP + 12
NEWLN $=$ NEWLN +16
NEWAR $=$ NEWAR + 5
/COM COPY CELLS TO MAKE GRID PANEL
/COM THIS COPIES THE AREAS
ALLSEL, ALL, ALL
! Copy
AGEN, CELL_X,ALL, , , PAN_WIDE, 0, 0, , 1
ALLSEL, ALL, ALL
AGEN, CELL_Y,ALL, , , 0, PAN_WIDE, 0, , 1
NEWKP $=$ NEWKP*CELL_X*CELL_Y+1
NEWLN $=$ NEWLN*CELL_X*CELL_Y+1
NEWAR $=$ NEWAR*CELL_X*CELL_Y+1
NUMMRG, KP, PAN_TALL*. 0001
/COM MESH THE AREAS
! Use mapped meshing so our line specs will stick
MSHKEY, 1
! Mesh all areas
AMESH, ALL
! To be safe, we can put the new nodes and element numbers well ahead
NEWEL =
$\left(C E L L \_X\right) *\left(C E L L \_Y\right) *\left(4 *\left(E L M \_W I D E+2\right) *\left(2 * I L Z \_T A L L+N L Z \_T A L L\right)+\left(E L M \_W I D E+2\right) *\left(E L M \_W I D E+\right.\right.$
2))
NEWND = NEWEL*8

```
*IF,MASSES,EQ,TRUE,THEN ! If we want masses, run this code.
/COM *********************************************
/COM **** ADD TOWER AND CALORIMETER MASSES ****
/COM ******************************************
! This section places calorimeter masses at the corners of each grid
! cell where they would be attached, and tower masses along the top
! perimeter of the cell where the towers would be attached
/COM MESH KEYPOINTS THAT SHOULD HAVE MASSES
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the old KPs)
NUMSTR,KP,NEWKP
K,,PAN_THCK/2,0,ILZ_DEEP
K,,(PAN_WIDE-PAN_THCK/2),0,ILZ_DEEP
K,,PAN_THCK/2,PAN_WIDE,ILZ_DEEP
K,,(PAN_WIDE-PAN_THCK/2),PAN_WIDE,ILZ_DEEP
K,,0,PAN_THCK/2,ILZ_DEEP
```

```
K,,0,(PAN_WIDE-PAN_THCK/2),ILZ_DEEP
K, ,PAN_WIDE,PAN_THCK/2,ILZ_DEEP
K,,PAN_WIDE,(PAN_WIDE-PAN_THCK/2),ILZ_DEEP
! Select all the keypoints and specify that mass elements will be
! generated off them
ALLSEL,ALL,KP
KATT,MAT_ALUM,R_CAL,1
! Mesh only the keypoints we just made
KMESH,NEWKP,NEWKP+7
! Merge them with previous keypoints so all will be attached to areas
! NUMMRG,KP,PAN_TALL*.0001,
/COM SPECIFY TOWER MASSES
! How many keypoints are there so far? At most this many
NEWKP = NEWKP + 8
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR, KP,NEWKP
K, ,PAN_THCK/2,0,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP,,,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,0,1, ,
NEWKP2 = NEWKP+2*ELM_WIDE+1
NUMSTR,KP,NEWKP2
K,,PAN_THCK/2,PAN_WIDE,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP2,,,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,0,1,,
NEWKP2 = NEWKP+2*(2*ELM_WIDE+1)
NUMSTR,KP,NEWKP2
K, 0,PAN_THCK/2,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP2,,,0,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,1, ,
NEWKP2 = NEWKP+3*(2*ELM_WIDE+1)
NUMSTR,KP,NEWKP2
K,,PAN_WIDE,PAN_THCK/2,PAN_TALL
KGEN,2*ELM_WIDE+1,NEWKP2,,,0,(PAN_WIDE-PAN_THCK)/(2*ELM_WIDE),0,1,,
! Select all the keypoints and specify that mass elements will be
! generated off them
ALLSEL,ALL,KP
KATT,MAT_ALUM, R_TOWER,1
! Mesh the ones we want meshed
KMESH,NEWKP,NEWKP + 4* (2*ELM_WIDE+1)
! Merge them with previous keypoints so all will be attached to areas
! NUMMRG,KP,PAN_TALL*.0001,
! Copy the mass elements (only)
ESEL,S,TYPE, , 1
EGEN,CELL_X,4*(4+(ELM_WIDE*2+1)+2),ALL,,,r,, ,,PAN_WIDE,0,0
! 4 walls*(4nodes on ilz+nodes on main panel+calorimeter masses)
ESEL,S,TYPE,,1
EGEN,CELL_Y,CELL_X*4*(4+(ELM_WIDE*2+1) +2),ALL,r,r,r,,0,PAN_WIDE,0
! Update element and keypoint counter
NEWEL = NEWEL + CELL_Y*CELL_X*4*(4+(ELM_WIDE*2+1) +2)
NEWKP = NEWKP + 4*(4+(ELM_WIDE* 2+1) +2)
NEWND = NEWND + CELL_Y*CELL_X*4*(4+(ELM_WIDE*2+1) +2)
*ENDIF ! End of code that adds masses
*IF,INCLGRID,EQ,TRUE,THEN ! If we want an aluminum grid, execute this code
```

```
/COM **************************************************************
/COM *** MAKE AN ALUMINUM GRID ON THE TOP OF THE COMPOSITE GRID ***
/COM **************************************************************
! The aluminum flange at the top of the grid cells provides an attachment point
! for the towers, something to contain the heat pipes, and adds stiffness
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR,KP,NEWKP
! First do the x direction
! Keypoints
K, 0,0,PAN_TALL
K, ,PAN_THCK/2,0,PAN_TALL
K,,PAN_WIDE-PAN_THCK/2,0,PAN_TALL
K,,PAN_WIDE,0,PAN_TALL
! Lines
NUMSTR, LINE, NEWLN
L,NEWKP,NEWKP+1,1
L,NEWKP +1,NEWKP + 2, ELM_WIDE
L,NEWKP + 2,NEWKP + 3, 1
! Orientation keypoint
K, ,PAN_WIDE/2,0,0
! Select lines and assign them properties and orientation keypoints
LSEL, LINE, ,NEWLN, NEWLN+2, , ,
LATT,MAT_ALUM, R_BEAM, 2, ,NEWKP + 4, , 1
! Mesh the lines
NUMSTR, ELEM, NEWEL
NUMSTR,NODE, NEWND
LMESH,NEWLN, NEWLN+2, ,
! Now copy the elements
ESEL,S,ELEM, NEWEL,NEWEL+2+ELM_WIDE-1, ,
EGEN, CELL_X, (2+ELM_WIDE)*3+1,ALL, , r, r, , ,PAN_WIDE, 0,0
ESEL,S,ELEM, NEWEL,NEWEL+ (2+ELM_WIDE) *CELL_X-1, ,
EGEN, CELL_Y+1,CELL_X* ((2+ELM_WIDE)*3+1),ALL,r,r,r, , 0,PAN_WIDE,0
NEWEL = NEWEL + ((CELL_Y+1)*CELL_X)* (1+2* (2+ELM_WIDE) )
NEWND = NEWND + ((CELL_Y+1)*CELL_X)* (1+3* (2+ELM_WIDE)) +1
! Now do the y direction
! Keypoints
NEWKP = NEWKP+5
NUMSTR, KP , NEWKP
K, , 0,0,PAN_TALL
K, , 0,PAN_THCK/2,PAN_TALL
K, ,0,PAN_WIDE-PAN_THCK/2,PAN_TALL
K, , O,PAN_WIDE,PAN_TALL
! Lines
NEWLN = NEWLN+3
NUMSTR, LINE, NEWLN
L,NEWKP,NEWKP +1,1
L,NEWKP +1,NEWKP + 2, ELM_WIDE
L,NEWKP + 2,NEWKP + 3, 1
! Orientation keypoint
K, ,0,PAN_WIDE/2,0
! Select lines and assign them properties and orientation keypoints
LSEL, LINE, ,NEWLN, NEWLN+2, , ,
```

```
LATT,MAT_ALUM, R_BEAM, 2, ,NEWKP + 4,NEWKP +4,1
! Mesh the lines
NUMSTR,ELEM, NEWEL
NUMSTR,NODE,NEWND
LMESH,NEWLN,NEWLN+2, ,
! Now copy the elements
ESEL,S,ELEM, NEWEL,NEWEL+2+ELM_WIDE-1, ,
EGEN, CELL_Y, (2+ELM_WIDE)*3+1,ALL,,, ,, , , 0,PAN_WIDE,0
ESEL,S,ELEM, NEWEL,NEWEL+(2+ELM_WIDE) *CELL_Y-1, ,
EGEN,CELL_X+1,CELL_Y*((2+ELM_WIDE)*3+1),ALL,r,r,r,,PAN_WIDE,0,0
NEWEL = NEWEL + CELL_Y*(CELL_X+1)* (1+2* (2+ELM_WIDE))
NEWND = NEWND + CELL_Y* (CELL_X+1)* (1+2* (2+ELM_WIDE))* * +1
NEWKP = NEWKP + 5
NEWLN = NEWLN + 3
*ENDIF! End code for making aluminum grid.
```

```
/COM ******************************
```

/COM ******************************
/COM **** PUT IT ALL TOGETHER ****
/COM **** PUT IT ALL TOGETHER ****
/COM ******************************

```
! Merge all the areas and keypoints and lines for everything created so far
ALLSEL, ALL, ALL
NUMMRG, NODE, PAN_TALL*. 0001 ,
! Merge nodes
NUMMRG, NODE, PAN_TALL*. 0001 ,
\(/ \mathrm{COM} * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ~+~\)
/COM ** ADD GLAST BOUNDARY CONDITIONS **
\(/ \mathrm{COM} * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * ~+~\)
!/COM CREATE GRAVITY, 7.0 Gee
! ACEL, 0, 9.8*7, 0,
/COM NOW WE CAN FIX THE STRUCTURAL BOUNDARY CONDITIONS
! Depending on which \(B C\) is specified in the beginning of the program,
! different BC's will be applied
*IF, EIGHTUZ, EQ, TRUE, THEN

/COM *** EIGHT POINTS SUPPORTED IN Z DIRECTION ONLY ***

/COM DEFINE THE LOCATION OF THE SUPPORT POINTS
! The strategy here is to make new keypoints where we want
! BC's, assign the BC's, then merge the keypoints into the
! model.
! Constraining just one node for each support point causes point stresses ! which lead to incorrect values. Instead, we take several nodes that are ! within millimeters of each other, support one, and make the rest rigid ! with respect to the supported one. This spreads the load out slightly and
! creates a more realistic spread of stress.
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR, KP, NEWKP
K, ,PAN_WIDE, 0, 0
K, ,PAN_WIDE*3,0,0
K, ,PAN_WIDE, PAN_WIDE*4, 0
K, ,PAN_WIDE*3, PAN_WIDE*4, 0
K, 0, PAN_WIDE, 0
K, , 0, PAN_WIDE*3, 0
K, ,PAN_WIDE*4,PAN_WIDE, 0
K, ,PAN_WIDE*4, PAN_WIDE*3,0
! These are the keypoints at the top of the aluminum bosses
K, ,PAN_WIDE, 0,ILZ_DEEP
K, , PAN_WIDE*3, 0, ILZ_DEEP
K, ,PAN_WIDE,PAN_WIDE*4,ILZ_DEEP
K, ,PAN_WIDE*3, PAN_WIDE*4, ILZ_DEEP
K, , 0, PAN_WIDE, ILZ_DEEP
K, , 0, PAN_WIDE*3, ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE,ILZ_DEEP
K, ,PAN_WIDE*4, PAN_WIDE*3, ILZ_DEEP
! These are the keypoints at the inside of the aluminum bosses
K, ,PAN_WIDE,PAN_THCK/2,ILZ_DEEP
K, , PAN_WIDE*3, PAN_THCK/2, ILZ_DEEP
K, ,PAN_WIDE,PAN_WIDE*4-PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*3,PAN_WIDE*4-PAN_THCK/2,ILZ_DEEP
K, ,PAN_THCK/2,PAN_WIDE,ILZ_DEEP
K, ,PAN_THCK/2,PAN_WIDE*3,ILZ_DEEP
K, ,PAN_WIDE*4-PAN_THCK/2,PAN_WIDE,ILZ_DEEP
K, ,PAN_WIDE*4-PAN_THCK/2,PAN_WIDE*3, ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE+PAN_THCK/2,0,ILZ_DEEP
K, ,PAN_WIDE*3+PAN_THCK/2, 0, ILZ_DEEP
K, ,PAN_WIDE+PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP
K, ,PAN_WIDE*3+PAN_THCK/2,PAN_WIDE*4, ILZ_DEEP
K, , 0, PAN_WIDE+PAN_THCK/2,ILZ_DEEP
K, 0, PAN_WIDE*3+PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE+PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4, PAN_WIDE*3+PAN_THCK/2, ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE-PAN_THCK/2,0,ILZ_DEEP
K, ,PAN_WIDE*3-PAN_THCK/2, 0, ILZ_DEEP
K, ,PAN_WIDE-PAN_THCK/2,PAN_WIDE*4,ILZ_DEEP
K, ,PAN_WIDE*3-PAN_THCK/2,PAN_WIDE*4, ILZ_DEEP
K, , 0, PAN_WIDE-PAN_THCK/2,ILZ_DEEP
K, 0, PAN_WIDE*3-PAN_THCK/2, ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE-PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4, PAN_WIDE*3-PAN_THCK/2, ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes K, ,PAN_WIDE+PAN_THCK/2,0,0
K, ,PAN_WIDE*3+PAN_THCK/2, 0, 0
```

K,,PAN_WIDE+PAN_THCK/2,PAN_WIDE*4,0
K,,PAN_WIDE*3+PAN_THCK/2,PAN_WIDE*4,0
K,,0,PAN_WIDE+PAN_THCK/2,0
K,,0,PAN_WIDE*3+PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE+PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE*3+PAN_THCK/2,0
! These are the keypoints at the edges of the interlace nodes
K,,PAN_WIDE-PAN_THCK/2,0,0
K,,PAN_WIDE*3-PAN_THCK/2,0,0
K,,PAN_WIDE-PAN_THCK/2,PAN_WIDE * 4,0
K,,PAN_WIDE*3-PAN_THCK/2,PAN_WIDE*4,0
K, ,0,PAN_WIDE-PAN_THCK/2,0
K,,0,PAN_WIDE*3-PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE-PAN_THCK/2,0
K,,PAN_WIDE*4,PAN_WIDE*3-PAN_THCK/2,0
! Now make new nodes at all these keypoints so we can use the
! CERIG command to make them rigid
! Start numbering them at some huge number
NUMCMP,NODE
NUMSTR,NODE,NEWND
KSEL,,,,NEWKP,NEWKP+55 ! Select the keypoints we just made
NKPT,,ALL ! Create nodes at all selected keypoints
! Now rigidly attach the top to the bottom and inside of the boss nodes
*DO,N,0,7
CERIG,NEWND+N,NEWND+8+N,ALL
CERIG,NEWND+N,NEWND+16+N,ALL
CERIG,NEWND+N,NEWND+24+N,ALL
CERIG,NEWND+N,NEWND+32+N,ALL
CERIG,NEWND+N,NEWND+40+N,ALL
CERIG,NEWND+N,NEWND+48+N,ALL
*ENDDO
! Select the keypoints at the bottom
KSEL,S,KP, ,NEWKP,NEWKP+7
! This is the BC where all 8 are only constrained in the "Y" direction
DK,ALL, ,0, ,1,UZ,,, , , ,
! Merge nodes so the old nodes take on the properties we've assigned to
! the new ones that overlap them
NUMMERG,NODE,PAN_TALL*.0001, , ,HIGH
! Select all the keypoints again so we can merge the BC KPs
ALLSEL,ALL,KP
! Merge keypoints
NUMMERG,KP,PAN_TALL*.0001
! Select everything so it's there for the solution
ALLSEL,ALL,ALL
*ENDIF! End 8 node UZ support
*IF,FOURUZ,EQ,TRUE,THEN
/COM **************************************************
/COM *** FOUR POINTS SUPPORTED IN Z DIRECTION ONLY ***
/COM ****************************************************
/COM DEFINE THE LOCATION OF THE SUPPORT POINTS
! The strategy here is to make new keypoints where we want

```
! BC's, assign the BC's, then merge the keypoints into the
! model. More flexible than having to know which KPs
! Assign new keypoints with numbers starting at this number
! (the area copying operation messes up the order of the KPs)
NUMSTR, KP, NEWKP
K, ,PAN_WIDE*2,0,0
K, ,PAN_WIDE*2,PAN_WIDE*4, 0
K, , 0, PAN_WIDE*2,0
K, ,PAN_WIDE*4, PAN_WIDE*2, 0
! These are the keypoints at the top of the aluminum bosses
K, , PAN_WIDE*2, 0, ILZ_DEEP
K, ,PAN_WIDE*2,PAN_WIDE*4, ILZ_DEEP
K, , 0, PAN_WIDE*2,ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE*2,ILZ_DEEP
! These are the keypoints at the inside of the aluminum bosses
K, ,PAN_WIDE*2, PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*2,PAN_WIDE*4-PAN_THCK/2,ILZ_DEEP
K, ,PAN_THCK/2,PAN_WIDE*2,ILZ_DEEP
K, ,PAN_WIDE*4-PAN_THCK/2,PAN_WIDE*2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE*2+PAN_THCK/2,0,ILZ_DEEP
K, ,PAN_WIDE*2+PAN_THCK/2,PAN_WIDE*4, ILZ_DEEP
K, , 0, PAN_WIDE*2+PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4, PAN_WIDE*2+PAN_THCK/2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE*2-PAN_THCK/2,0,ILZ_DEEP
K, ,PAN_WIDE*2-PAN_THCK/2,PAN_WIDE*4, ILZ_DEEP
K, 0, PAN_WIDE*2-PAN_THCK/2,ILZ_DEEP
K, ,PAN_WIDE*4,PAN_WIDE*2-PAN_THCK/2,ILZ_DEEP
! These are the keypoints at the edges of the interlace nodes
K, PAN_WIDE*2+PAN_THCK/2,0,0
K, ,PAN_WIDE*2+PAN_THCK/2,PAN_WIDE*4,0
K, 0, PAN_WIDE*2+PAN_THCK/2, 0
K, ,PAN_WIDE*4,PAN_WIDE*2+PAN_THCK/2,0
! These are the keypoints at the edges of the interlace nodes
K, ,PAN_WIDE*2-PAN_THCK/2,0,0
K, ,PAN_WIDE*2-PAN_THCK/2,PAN_WIDE*4, 0
K, 0, PAN_WIDE*2-PAN_THCK/2, 0
K, PAN_WIDE*4, PAN_WIDE*2-PAN_THCK/2,0
! Now make new nodes at all these keypoints so we can use the CERIG command
! Start numbering them at some huge number
NUMCMP, NODE
NUMSTR, NODE, NEWND
KSEL, , , NEWKP,NEWKP+27 ! Select the keypoints we just made
NKPT, ALL ! Create nodes at all selected keypoints
! Now rigidly attach the top to the bottom and inside of the boss nodes *DO, N, 0, 3
CERIG, NEWND+N, NEWND \(+4+\mathrm{N}\), ALL
```

CERIG,NEWND+N,NEWND+8+N,ALL
CERIG,NEWND+N,NEWND+12+N,ALL
CERIG,NEWND+N,NEWND+16+N,ALL
CERIG,NEWND+N,NEWND+20+N,ALL
CERIG,NEWND+N,NEWND+24+N,ALL
*ENDDO

```
! Select the keypoints at the bottom
KSEL, S, KP, ,NEWKP, NEWKP+3
! This is the \(B C\) where all 8 are only constrained in \(Y\)
DK,ALL, ,0, \(1, \mathrm{UZ}\), , , ,
! Merge nodes
NUMMERG, NODE, PAN_TALL*. 0001, , , HIGH
! Select all the keypoints again so we can merge the BC KPs
ALLSEL, ALL, KP
! Merge keypoints
NUMMERG, KP, PAN_TALL*. 0001
! Select everything so it's there for the solution
ALLSEL, ALL, ALL
*ENDIF ! End 4 node UZ support
```

/COM ******************************************************
/COM *** A PROGRAM FOR FINDING FAILURE STRENGTH RATIOS ***
/COM *****************************************************
! 12/11/00
/COM Takes the built model, applies load, and returns failure
/COM strength ratios
! This program is tailored to walls that are six layers
! thick, but can be easily modified by altering the
! section below where the real constants are redefined.

```
/PREP 7
/COM CREATE A DIMENSIONED ARRAY OF ANGLES
! These values will serve as lookups for the different possible angles
! of plies in a layup
*DIM, WALLNGL, ARRAY, 8
*DIM, CORENGL, ARRAY, 9
*DIM, WALLNM, CHAR, 8
*DIM, CORENM, CHAR, 9
! And some numbers to be used in file names
*DIM, NUMS, CHAR, 8
*SET, NUMS (1), '000', '001', '002', '003', '004', '005', '006','007'
! In the following assignments there is a code
    \(900=0 / 90\) 's
    \(104=0 / 45 /-45 / 90\) 's
    \(103=0 / 60 /-60\) 's
*SET,WALLNGL (1) , 0, 15, 30, 45, 60, 75, 90, 900
*SET, CORENGL (1) , 0, 15, 30, 45, 60, 75, 90, 900
*SET, CORENGL (9), 104
*SET,WALLNM (1), '0','15','30','45','60','75','90', '0_90'
*SET, CORENM (1), '0','15','30','45','60','75','90','0_90'
*SET, CORENM (9), 'quasi'
```

/COM APPLY DESIRED LAYUP
WALL = 2
CORE = 5
! These decide whether to use an angle ply, 0/90, or
! quasiisotropic option

```
/COM DEAL WITH THE WALLS
*IF, WALLNGL (WALL) ,EQ, 900,THEN
/COM WALL IS 0/90s
! If the walls are 0/90's then modify the non-interlaced elements
RMODIF, 1, 13, MAT_T300,0, PLY_THCK,
RMODIF,1,16,MAT_T300,0,PLY_THCK,
RMODIF,1,19,MAT_T300,90,PLY_THCK,
RMODIF,1,22,MAT_T300,90,PLY_THCK,
RMODIF,1,25,MAT_T300,0,PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
RMODIF,1,67,MAT_T300,0,PLY_THCK,
RMODIF,1,70,MAT_T300,0,PLY_THCK,
RMODIF,1,73, MAT_T300,90,PLY_THCK,
RMODIF, 1, 76, MAT_T300,90,PLY_THCK,
RMODIF,1,79,MAT_T300,0,PLY_THCK,
RMODIF, 1, 82, MAT_T300, \(^{0}\), PLY_THCK,
! and modify the interlaced elements
RMODIF, 2, 13, MAT_T300,0,PLY_THCK,
RMODIF, 2, 16, MAT_T300,0, PLY_THCK,
RMODIF, 2, 19, MAT_T300,90,PLY_THCK,
RMODIF, 2, 22, MAT_T300,90,PLY_THCK,
RMODIF, 2, 25, MAT_T300,0, PLY_THCK,
RMODIF, 2, 28, MAT_T300,0,PLY_THCK,
RMODIF, 2, 34, MAT_T300,0, PLY_THCK,
RMODIF, 2, 37, MAT_T300,0,PLY_THCK,
RMODIF, 2, 40, MAT_T300,90,PLY_THCK,
RMODIF, 2, 43, MAT_T300,90,PLY_THCK,
RMODIF, 2, 46, MAT_T300,0,PLY_THCK,
RMODIF, 2, 49, MAT_T 300,0, PLY_THCK,
*ELSEIF,WALLNGL (WALL) , EQ, 103, THEN
/COM WALL IS 0/60/-60s
! If the walls are 0/90's then modify the non-interlaced elements
RMODIF, 1,13, MAT_T300,0,PLY_THCK,
RMODIF, 1, 16, MAT_T300,60,PLY_THCK,
RMODIF,1,19,MAT_T300,-60,PLY_THCK,
RMODIF,1,22,MAT_T300,-60,PLY_THCK,
RMODIF,1,25,MAT_T300,60,PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
RMODIF,1,67,MAT_T300,0,PLY_THCK,
RMODIF, 1, 70, MAT_T300,60,PLY_THCK,
RMODIF,1,73, MAT_T300,-60,PLY_THCK,
RMODIF, 1,76, MAT_T300,-60,PLY_THCK,
RMODIF, 1, 79, MAT_T300,60, PLY_THCK,
RMODIF,1,82,MAT_T300,0,PLY_THCK,
```

! and modify the interlaced elements
RMODIF,2,13,MAT_T300,0,PLY_THCK,
RMODIF,2,16,MAT_T300,60,PLY_THCK,
RMODIF,2,19,MAT_T300,-60,PLY_THCK,
RMODIF,2,22,MAT_T300,-60,PLY_THCK,
RMODIF,2,25,MAT_T300,60,PLY_THCK,
RMODIF,2,28,MAT_T300,0,PLY_THCK,
RMODIF,2,34,MAT_T300,0,PLY_THCK,
RMODIF,2,37,MAT_T300,60,PLY_THCK,
RMODIF,2,40,MAT_T300,-60,PLY_THCK,
RMODIF,2,43,MAT_T300,-60,PLY_THCK,
RMODIF,2,46,MAT_T300,60,PLY_THCK,
RMODIF,2,49,MAT_T300,0,PLY_THCK,
*ELSE ! Else we use just the angles
/COM WALL IS ANGLES
WALLNGL1 = WALLNGL (WALL)
WALLNGL2 = -WALLNGL1
RMODIF,1,13,MAT_T300,0,PLY_THCK,
RMODIF,1,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,19,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,22,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,25,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,28,MAT_T300,0,PLY_THCK,
RMODIF,1,67,MAT_T300,0,PLY_THCK,
RMODIF,1,70,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,73,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,76,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,1,79,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,1,82,MAT_T300,0,PLY_THCK,
! and modify the interlaced elements
RMODIF,2,13,MAT_T300,0,PLY_THCK,
RMODIF,2,16,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,19,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,22,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,25,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,28,MAT_T300,0,PLY_THCK,
RMODIF,2,34,MAT_T300,0,PLY_THCK,
RMODIF,2,37,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,40,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,43,MAT_T300,WALLNGL1,PLY_THCK,
RMODIF,2,46,MAT_T300,WALLNGL2,PLY_THCK,
RMODIF,2,49,MAT_T300,0,PLY_THCK,
*ENDIF ! Wall

```
/COM NOW DEAL WITH CORE
*IF, CORENGL (CORE) , EQ, 900, THEN
! If it's 0/90 layup
/COM CORE IS 0/90
CORENGL1 \(=90\)
```

CORENGL2 = 0
RMODIF,1,31,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,34,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,37,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,40,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,43,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,46,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,49,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,52,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,55,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,58,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,61,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,64,MAT_T300,CORENGL1,PLY_THCK,
*ELSEIF,CORENGL (CORE),EQ,103
/COM CORE IS QUASI
! If it's quasiisotropic with 0/60/-60
RMODIF,1,31,MAT_T300,0,PLY_THCK,
RMODIF,1,34,MAT_T300,60,PLY_THCK,
RMODIF,1,37,MAT_T300,-60,PLY_THCK,
RMODIF,1,40,MAT_T300,-60,PLY_THCK,
RMODIF,1,43,MAT_T300,60,PLY_THCK,
RMODIF,1,46,MAT_T300,0,PLY_THCK,
RMODIF,1,49,MAT_T300,0,PLY_THCK,
RMODIF,1,52,MAT_T300,60,PLY_THCK,
RMODIF,1,55,MAT_T300,-60,PLY_THCK,
RMODIF,1,58,MAT_T300,-60,PLY_THCK,
RMODIF,1,61,MAT_T300,60,PLY_THCK,
RMODIF,1,64,MAT_T300,0,PLY_THCK,

```
*ELSE ! Else we use just the angles
/COM CORE IS ANGLES
CORENGL1 = CORENGL (CORE)
CORENGL2 = -CORENGL1
RMODIF,1,31,MAT_T300, CORENGL1, PLY_THCK,
RMODIF, 1, 34, MAT_T300, CORENGL2,PLY_THCK,
RMODIF, 1, 37, MAT_T300, CORENGL1, PLY_THCK,
RMODIF,1,40,MAT_T300,CORENGL2,PLY_THCK,
RMODIF,1,43,MAT_T300,CORENGL1, PLY_THCK,
RMODIF,1,46,MAT_T300, CORENGL2, PLY_THCK,
RMODIF,1,49,MAT_T300,CORENGL2, PLY_THCK,
RMODIF,1,52,MAT_T300,CORENGL1,PLY_THCK,
RMODIF, 1,55, MAT_T300, CORENGL2,PLY_THCK,
RMODIF,1,58,MAT_T300,CORENGL1,PLY_THCK,
RMODIF,1,61,MAT_T300, CORENGL2, PLY_THCK,
RMODIF,1,64,MAT_T300,CORENGL1,PLY_THCK,
*ENDIF ! Core
/COM NOW WE GO AHEAD AND SOLVE IT
/SOLU
/eof
! The code stops running at this point and the user must manually
! select and begin a static solution.

\section*{A. 3 THERMAL ANALYSIS PROGRAM}
```

/COM,ANSYS RELEASE 5.6 UP19991022 19:29:20 04/12/2000
/PREP7
/COM PHYSICS ENVIRONMENTS USED TO SOLVE GLAST GRID THERMAL DISTORTION
! 9/26/00 - Michael Hicks - Stanford University/SLAC
! This program uses ANSYS physics environments commands to couple a
! thermal and mechanical analysis of the GLAST grid. First, a
universal
! model is built. Thermal properties and boundary conditions are
applied,
! and the thermal model is saved. Then the appropriate mechanical
boundary
! conditions and properties are applied and saved. The thermal model
can
! then be run to find temperature distribution, and the results mapped
to
! the structural model to find thermal distortion.
! Because ANSYS has no laminate elements capable of calculating thermal
! conductivity, this model uses linear shell elements for which the
! laminate properties are calculated in the program using ply
properties
! and standard transformations.
! The program is designed to loop through many combinations of wall and
! core laminate layup.
/COM CREATE A DIMENSIONED ARRAY OF ANGLES
! These will be used to assign layups in the loop
*DIM,WALLNGL,ARRAY,8
*DIM, CORENGL, ARRAY,9
*DIM,WALLNM, CHAR,8
*DIM, CORENM, CHAR,9
! These numbers are used when generating filenames for saved results
*DIM, NUMS,CHAR,8
*SET,NUMS(1),'000','001','002','003','004','005','006','007'
! In the following assignments there is a code
! 900 = 0/90's
! 104 = 0/45/-45/90's
! 103 = 0/60/-60's

```
*SET, WALLNGL (1) , 0, 15, 30, 45, 60, 75, 90, 900
*SET, CORENGL (1) , 0, 15, 30, 45, 60, 75, 90, 900
*SET, CORENGL (9), 104
*SET,WALLNM (1), '0','15','30','45','60','75','90','0_90'
*SET, CORENM (1), '0','15','30','45', '60','75','90','0_90'
*SET, CORENM (9), 'quasi'
```

! Use degrees for the angles
*AFUN,DEG

```
/COM DEFINE THE MODEL
! Meshing
ELM_WIDE=4 ! Number of elements across one panel (/2)
ELM_TALL=4 ! Number of elements up one panel (/2)
ILZ_TALL=1 ! Number of elements the ilz is deep on one side
! Geometry
PAN_WIDE=. 372 ! Panel width
PAN_TALL=. 24 ! Panel height
PAN_THCK=.006 ! Panel thickness
TOP_WIDE=. 0254 ! Top flange width
TOP_TALL=.0204 ! Top flange height - 25.4 mm minus 5 mm to approx
pipe
! Create mass element
ET, 1, MASS21
! Make it not have a rotational inertia
KEYOPT,1,2,0
KEYOPT,1,3,2
! Create 2 node beam element
ET, 2, BEAM188
! Create linear-layered shell element
! ET,3,SHELL63
! Create thermal shell element
ET, 3, SHELL57
/COM MATERIALS DEFINED
! A little math is going to be necessary to calculate laminate
! properties and enter them properly
! Prepreg material
! YS90A
\(\operatorname{ExP}=520 \mathrm{E} 9 \quad\) ! Engineering constants
\(\mathrm{EyP}=5.7 \mathrm{E} 9\)
\(\mathrm{vxP}=.3\)
vyP = vxP*EyP/ExP
EssP \(=5.1 \mathrm{E} 9\)
KxxP \(=304 \quad\) ! Conductivity
\(\mathrm{KyyP}=.72\)
AlphxxP = -1.4E-6 ! Coefficienct of thermal expansion
AlphyyP \(=33 \mathrm{E}-6\)
! Interlace material
! YS90A fiber
Exf = 880E9
Eyf = 7.8E9
vxf \(=.79\)
Exyf \(=17.2 \mathrm{E} 9\)
Kxxf \(=500\)
Kyyf \(=.72\)
```

Alphxxf = -1.5E-6
Alphyyf = 22E-6
! Standard epoxy matrix
Exm = 3.56E9
Eym = 3.56E9
vxm = . 3
Exym = 1.37E9
Kxxm = 10
Kyym = 10
Alphxxm = 60E-6
Alphyym = 60E-6
! Interlace combination
vf = .4 ! Volume fraction
! These formulas are from micromechanics
Exi = 1/(vf+1*(1-vf))*(vf*Exf+Exm*(1-vf))
Eyi = 1/(1/(vf+.5*(1-vf))*(vf/Eyf+.5*(1-vf)/Eym))
vxi = 1/(vf+1*(1-vf))*(vf*vxf+1*(1-vf)*vxm)
vyi = vxi*Eyi/Exi
Essi = 1/(1/(vf+.5*(1-vf))*(vf/Exyf+.5*(1-vf)/Exym))
Kxxi = Kxxf*vf+Kxxm*(1-vf)
Kyyi = 1/(vf/Kyyf+(1-vf)/Kyym)
Alphxxi = (Alphxxf+(1-vf)/vf*Exm/Exf*Alphxxm)/(1+(1-vf)/vf*Exm/Exf)
Alphyyi = 2/(1/Alphyyf+1/Alphyym)
! Stiffness of interlace
m = 1/(1-vxi*vyi)
QxxI = m*Exi
QyyI = m*Eyi
QxyI = m*vxi*Eyi
QssI = Essi
! Calculate Stiffnesses of plies
m = 1/(1-vxP*vyP)
Qxx = m*ExP
Qyy = m*EyP
Qxy = m*vxP*EyP
Qss = EssP
! Now the invariants
U1 = (3*Qxx+3*Qyy+2*Qxy+4*Qss)/8
U2 = (Qxx-Qyy)/2
U3 = (Qxx+Qyy-2*Qxy-4*Qss)/8
U4 = (Qxx+Qyy+6*Qxy-4*Qss)/8
U5 = (Qxx+Qyy-2*Qxy+4*Qss)/8
! Quasiisotropic CTE
AlphaQIP =
(.5* (U1+U2*Cos(2*45)+U3*Cos(4*45))*(AlphxxP+AlphyyP)*Sin(45)**2)
AlphaQIP = (AlphaQIP+.25*AlphxxP*Qxx+.25*AlphyyP*Qyy)/U1
! Now the stiffnesses from the invariants
Qxx = (U1+U2*Cos(0))
! Make Material 1 as Aluminum
! UIMP,1,EX, , ,76E9,
UIMP,1,KXX, , , 240,
! Make Material 2 "special" panel

```
```

UIMP,2,KXX, , , 240,
! +-45s of T300 material
!UIMP,3,KXX,KYY,KZZ,2.67,2.67,.72,
! Non-interlaced material
UIMP, 3,KXX,KYY,KZZ,152.4,152.4,.72,
! Interlaced material
UIMP,4,KXX,KYY,KZZ,188.12,51.26,.72,
! Make Material 5 1mm walls of T300, 4 mm wide of . 45 vf YS90
UIMP,5,KXX,KYY,KZZ,188.12,51.26,.72,
! Give names to the material numbers so it's easier to see
! what I'm doing
MAT_ALUM=1 ! Aluminum
MAT_TPAN=2 ! "Tower Panel", calculated properties of a tray sandwich
MAT_NILZ=3 ! Non-interlaced section of a rib
MAT_ILZ=4 ! Interlaced section of a rib
/COM REAL CONSTANTS DEFINED
! beams
R,4, , , , ,
! Aluminum wall panels for evaluating aluminum design
R,5,PAN_THCK,,,,,
! This is the constant for the top panel, it's 5.5 mm thick
R,6,.0055,,,,,
! Ilz wall panels
R,7,PAN_THCK, ,, ,,
! Nilz wall panels
R,8,PAN_THCK,,,,,
/COM CROSS SECTIONS DEFINED
SECTYPE, 1, BEAM, RECT, topflange
SECOFFSET, USER, 0, TOP_WIDE/2
SECDATA, TOP_TALL,TOP_WIDE,0,0,0,0,0,0,0,0
/COM MAKE THE RECTANGLE AND READY IT FOR MESHING
RECTNG,0,PAN_WIDE,0,PAN_TALL,
! This is what chooses the area in the GUI
CM,_Y,AREA
ASEL, , , ,
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
! This specifies mesh by material, real constant, element, and CS
AATT, MAT_ILZ, 7, 3, 0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
! Select top line of rectangle
CM,_Y,LINE
LSEL, , , , 3
CM,_Y1,LINE

```
```

CMSEL,S,_Y
!*
! Specify mesh as material, real constant, element type, orientation
keypoint
CMSEL,S,_Y1
LATT,MAT_ALUM, 4,2, , 1, ,1
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
! Choose the lines that go across for size definition
FLST,5,2,4,ORDE,2
! Select lines 1,3
FITEM,5,1
FITEM,5,3
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
! Define how many elements across
LESIZE,_Y1, , ,ELM_WIDE*2, , , , ,0
CMDELE,_Y
CMDELE,_Y1
!* Choose the vertical lines for size definition
FLST,5,2,4,ORDE,2
FITEM,5,2
FITEM,5,4
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
! Define how many element high
LESIZE,_Y1, , ,ELM_TALL*2, , , , ,0
CMDELE,_Y
CMDELE,_Y1
! Get ready to mesh area
MSHAPE,0,2D
MSHKEY,1
!*
CM,_Y,AREA
ASEL, , , , 1
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
! Mesh area
AMESH,_Y1
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
! Mesh the line
LMESH, 3
/UI,MESH,OFF
! Select the non-interlaced region so we can modify it to have
appropriate real constants

```
```

ESEL, (ELM_WIDE*2)*ILZ_TALL+1,(ELM_WIDE*2)*(ELM_TALL*2)-
(ELM_WIDE*2)*ILZ_TALL,,,
EMODIF,ALL,MAT,MAT_NILZ,
ALLSEL,ALL! ! Select everything back again
/COM COPY PANELS
! Once a single panel with appropriate elements has been made
! we can copy it to make ribs and then the entire grid
! This command makes the workplane visible
WPSTYLE,,,r,r,,1
! For some reason, the workplane is coordinate system 4, so
! when I make the active coordinate system the workplane, this
! is how to do it.
CSYS,4
/VIEW, 1 ,1,2,3
/ANG, 1
/REP,FAST
! Choose all the area as the object of the copy command
FLST,3,1,5,ORDE,1
FITEM, 3,1
! Now copy the area so we wind up with 4 total. Copy in the X
direction
AGEN,4,P51X, , ,PAN_WIDE, , , ,0
! Rotate the workplane by 90 degrees around it's y axis
wpro, ,,90.000000
! Choose all the areas that now exist as the objects for the next
command
FLST, 3, 4,5,ORDE,2
FITEM, 3,1
FITEM, 3,-4
! Transfer the coordinates of the areas from the rotated workplane
! to the non-rotated global coordinate system (CS = 0)
ATRAN,0,P51X, , , ,0,0
! Now we have a copy of the panels running perp to the originals
! Choose the original 4 areas and copy them in the -x direction of the
! current workplane.
FLST, 3,4,5,ORDE,2
FITEM,3,1
FITEM, 3,-4
! Copy them so we have 5 total
AGEN,5,P51X, , ,-PAN_WIDE, , , ,0
! Rotate the workplane back (this is just because I've had weird bug
! trouble copying anything in a non-x direction - paranoid Michael)
wpro,,,-90.000000
! Choose the perpendicular panels
FLST, 3,4,5,ORDE,2
FITEM, 3,5
FITEM, 3,-8
! Copy them so we have 5 total
AGEN,5,P51X, , ,PAN_WIDE, , , ,0
/COM AND NOW WE MAKE THE TOP PANELS
! Move the workplane up to the top of the walls and rotate so that
! x-y is in the plane of the top panels
FLST, 2,1,8
FITEM,2,0,PAN_TALL,0

```
```

WPAVE,P51X
wpro,,-90.000000,
wpro,-90.000000, ,
! Make the 1st tracker panel area
RECTNG,0,PAN_WIDE,0,PAN_WIDE,
! Select the area
CM,_Y,AREA
ASEL, , , , 41
CM,_Y1,AREA
CMSEL,S,_Y
!*
CMSEL,S,_Y1
! Define it by material, real constant, element type, coordinate system
AATT, MAT_TPAN, 6, 3, 0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
! Select the lines around it's perimeter
FLST,5,4,4,ORDE,2
FITEM,5,161
FITEM,5,-164
CM,_Y,LINE
LSEL, , , ,P51X
CM,_Y1,LINE
CMSEL,r_Y
! Size the lines to have the right number of elements on edges
LESIZE,_Y1, , ,ELM_WIDE*2, , , , ,0
CMDELE,_Y
CMDELE,_Y1
! Choose the area to mesh
CM,_Y,AREA
ASEL, , , ,
4 1
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
! Mesh the blasted thing
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
! Copy in the X direction
FLST, 3,1,5,ORDE,1
FITEM, 3,41
AGEN,4,P51X, , ,PAN_WIDE, , , ,0
! Copy in the Y direction
FLST, 3,4,5,ORDE,2
FITEM, 3,41
FITEM, 3,-44
AGEN,4,P51X, , , ,PAN_WIDE, , ,0
/COM NEW SECTION. NOW WE'RE BUILDING THE MASS NODES
! Move the workplane back to global cartesian
WPCSYS,-1,0
! Calculate what node and element we're on here

```
```

! Total nodes is element wall nodes + orientation nodes of beams
! This is the recalculation based on linear elements
NEW_NODE=NEW_NODE+16*((ELM_WIDE*2+1)* (ELM_WIDE*2+1))
NEW_ELM=NEW_ELM+16*4*(ELM_WIDE*ELM_WIDE)

```
/COM ALL THE ELEMENTS ARE CREATED. NOW MERGE NODES AND KEYPOINTS
NUMMRG, NODE, , , LOW
NUMMRG, KP, , , ,LOW
/COM THERMAL BOUNDARY CONDITIONS
! Here are the heat loads we will be experiencing from the equipment
! Values are the watts that would go into a wall of a bay
TEM_HEAT \(=5.5 / 4\)
CAL_HEAT \(=7.4 / 4\)
SIU_HEAT \(=5 / 4\)
ACD_HEAT \(=14.5 / 4\)
! Here we select all the top lines and the bottom perimeter and make
them isothermal
FLST, 2, 56, 4, ORDE, 56
FITEM, 2,1
FITEM, 2, 3
FITEM, 2,5
FITEM, 2,7
FITEM, 2,9
FITEM, 2,11
FITEM, 2,13
FITEM, 2,15
FITEM, 2,17
FITEM, 2,19
FITEM, 2,21
FITEM,2,23
FITEM, 2,25
FITEM, 2, 27
FITEM, 2,29
FITEM, 2,31
FITEM, 2,35
FITEM, 2,39
FITEM, 2,43
FITEM, 2,47
FITEM, 2,51
FITEM, 2,55
FITEM, 2,59
FITEM, 2,63
FITEM, 2,67
FITEM, 2,71
FITEM, 2,75
FITEM, 2,79
FITEM, 2,81
FITEM, 2,83
FITEM, 2,85
FITEM, 2,87
FITEM, 2,89
FITEM, 2,91
```

FITEM,2,93
FITEM, 2,95
FITEM,2,99
FITEM,2,103
FITEM,2,107
FITEM,2,111
FITEM, 2,115
FITEM,2,119
FITEM,2,123
FITEM,2,127
FITEM,2,131
FITEM,2,135
FITEM, 2,139
FITEM,2,143
FITEM,2,145
FITEM,2,147
FITEM,2,149
FITEM, 2,151
FITEM, 2,153
FITEM,2,155
FITEM, 2,157
FITEM, 2,159
/GO
!*
DL,P51X, ,TEMP,0,1
! These are the heats going into the bottom lines
FLST,2,16,4,ORDE,16
FITEM,2,37
FITEM,2,41
FITEM,2,49
FITEM,2,53
FITEM,2,57
FITEM, 2,61
FITEM,2,69
FITEM,2,73
FITEM,2,101
FITEM,2,105
FITEM,2,113
FITEM, 2,117
FITEM,2,121
FITEM,2,125
FITEM,2,133
FITEM, 2,137
/GO
!*
SFL,P51X,HFLUX, (2* (CAL_HEAT+TEM_HEAT))/PAN_WIDE
FLST,2,4,4,ORDE,4
FITEM,2,45
FITEM,2,65
FITEM,2,109
FITEM,2,129
/GO
!*
SFL,P51X,HFLUX,(2* (CAL_HEAT+TEM_HEAT) +ACD_HEAT)/PAN_WIDE

```
```

FLST,2,4,4,ORDE,4
FITEM,2,33
FITEM, 2,77
FITEM, 2,97
FITEM,2,141
/GO
!*
SFL,P51X,HFLUX,(2* (CAL_HEAT+TEM_HEAT) +SIU_HEAT) /PAN_WIDE
/COM NOW THAT MODEL IS BUILT, START THE LOOPS FOR SOLUTION
! First orient it right for recording info
/AUTO, 1
/REP
/ANG,1,-70, XS,1
/REP,FAST
/COM LOOP THROUGH ALL DESIGNS
!DO,WALL,1,7 !1,8
!DO,CORE,1,9 !1,9
WALL = 7
CORE = 4
/COM CALCULATE ALL THE NEW LAMINATE PROPERTIES FOR THIS LOOP
! Now the stiffnesses from the invariants
! Wall stiffness
*IF,WALLNGL (WALL),EQ,900,THEN
QxxW = U1+U3
QyyW = U1+U3
QxyW = U4-U3
QssW = U5-U3
KxxW = KxxP/2+KyyP/2
KyyW = KxxP/2+KyyP/2
AlphxxW = AlphxxP/2+AlphyyP/2
AlphyyW = AlphxxP/2+AlphyyP/2
*ELSEIF,WALLNGL (WALL),EQ,104,THEN
QxxW = U1
QyyW = U1
QxyW = U4
QssW = U5
KxxW = KxxP/2+KyyP/2
KyyW = KxxP/2+KyyP/2
AlphxxW = AlphaQIP
AlphyyW = AlphaQIP
*ELSEIF,WALLNGL(WALL),EQ,103,THEN
QxxW = U1
QyyW = U1
QxyW = U4
QssW = U5
KxxW = KxxP/2+KyyP/2
KyyW = KxxP/2+KyyP/2
AlphxxW = AlphaQIP
AlphyyW = AlphaQIP
*ELSE
QxxW = (U1+U2*Cos(2*WALLNGL (WALL)) +U3* Cos(4*WALLNGL (WALL)))

```
```

QyyW = (U1-U2*Cos(2*WALLNGL (WALL)) +U3*Cos(4*WALLNGL (WALL)))
QxyW = (U4-U3*Cos(4*WALLNGL (WALL)))
QssW = (U5-U3*Cos(4*WALLNGL (WALL)))
KxxW = KxxP*Cos(WALLNGL (WALL))**2+KyyP*Sin(WALLNGL (WALL))**2
KyyW = KyyP*Cos(WALLNGL (WALL))**2+KxxP*Sin(WALLNGL (WALL))**2
AlphxxW = AlphxxP*Cos(WALLNGL (WALL)) **2+AlphyyP*Sin(WALLNGL (WALL)) **2
AlphyyW = AlphyyP*Cos(WALLNGL (WALL))**2+AlphxxP*Sin(WALLNGL (WALL)) **2
*ENDIF
! Core stiffness
*IF, CORENGL (CORE),EQ,900,THEN
QxxC = U1+U3
QyyC = U1+U3
QxyC = U4-U3
QssC = U5-U3
KxxC = KxxP/2+KyyP/2
KyyC = KxxP/2+KyyP/2
AlphxxC = AlphxxP/2+AlphyyP/2
AlphyyC = AlphxxP/2+AlphyyP/2
*ELSEIF,CORENGL (CORE),EQ,104,THEN
QxxC = U1
QyyC = U1
QxyC = U4
QssC = U5
KxxC = KxxP/2+KyyP/2
KyyC = KxxP/2+KyyP/2
AlphxxC = AlphaQIP
AlphyyC = AlphaQIP
*ELSEIF, CORENGL (CORE),EQ, 103,THEN
QxxC = U1
Qyyc = U1
QxyC = U4
QssC = U5
KxxC = KxxP/2+KyyP/2
KyyC = KxxP/2+KyyP/2
AlphxxC = AlphaQIP
AlphyyC = AlphaQIP
*ELSE
QxxC = (U1+U2* Cos (2*CORENGL (CORE)) +U3*Cos(4*CORENGL (CORE) ) )
QyyC = (U1-U2*Cos (2*CORENGL (CORE)) +U3*Cos(4*CORENGL (CORE)))
QxyC = (U4-U3*Cos(4*CORENGL (CORE)))
QssC = (U5-U3*Cos(4*CORENGL (CORE)))
KxxC = KxxP*Cos(CORENGL(CORE))**2+KyyP*Sin(CORENGL (CORE))**2
KyyC = KyyP*Cos(CORENGL (CORE))**2+KxxP*Sin(CORENGL (CORE))**2
AlphxxC = AlphxxP*Cos(CORENGL (CORE))**2+AlphyyP*Sin(CORENGL (CORE))**2
AlphyyC = AlphyyP*Cos(CORENGL (CORE))**2+AlphxxP*Sin(CORENGL(CORE))**2
*ENDIF
! Combinations
corefrac = (.006-2*4*.00025)/.006 ! Number of layers of wall
wallfrac = (2*4*.00025)/.006 ! affects fraction of cross-section
! Wall and core
QxxWC = QxxW*wallfrac+QxxC*corefrac
QyyWC = QyyW*wallfrac+QyyC*corefrac
QxyWC = QxyW*wallfrac+QxyC*corefrac
QssWC = QssW*wallfrac+QssC*corefrac
m = 1/(1-QxyWC*QxyWC/(QxxWC*QyyWC))

```
```

ExxWC = QxxWC/m
EyyWC = QyyWC/m
vxWC = QxyWC/QyyWC
EssWC = QssWC
KxxWC = KxxW*wallfrac+KxxC*corefrac
KyyWC = KyyW*wallfrac+KyyC*corefrac
AlphxxWC = (AlphxxW*wallfrac*QxxW+AlphxxC*corefrac*QxxC)/QxxWC
AlphyyWC = (AlphyyW*wallfrac*QyyW+AlphyyC*corefrac*QyyC)/QyyWC
! Wall and interlace
QxxWI = QxxW*wallfrac+QxxI*corefrac
QyyWI = QyyW*wallfrac+QyyI*corefrac
QxyWI = QxyW*wallfrac+QxyI*corefrac
QssWI = QssW*wallfrac+QssI*corefrac
m = 1/(1-QxyWI*QxyWI/(QxxWI*QyyWI))
ExxWI = QxxWI/m
EyyWI = QyyWI/m
vxWI = QxyWI/QyyWI
EssWI = QssWI
KxxWI = KxxW*wallfrac+Kxxi*corefrac
KyyWI = KyyW*wallfrac+Kyyi*corefrac
AlphxxWI = (AlphxxW*wallfrac*QxxW+Alphxxi*corefrac*QxxI)/QxxWI
AlphyyWI = (AlphyyW*wallfrac*QyyW+Alphyyi*corefrac*QyyI)/QyyWI
/COM THERMAL PROPERTIES DEFINED
/PREP7
! Redo new thermal properties
! Non-interlaced material
UIMP, 3, KXX, KYY,KZZ,KxxWC,KyyWc, . 72,
! Interlaced material
UIMP,4,KXX,KYY,KZZ,KxxWI,KyyWI, . 72,
! Write the thermal environment file and reset the physics environment
nsel,all
PHYSICS,WRITE,thermal
PHYSICS,CLEAR
/COM STRUCTURAL PHYSICS ENVIRONMENT BELOW
! Modify the element type of the shell
ET,3,SHELL63
/COM CHANGE THE STRUCTURAL MATERIALS
! Make Material 1 as Aluminum
UIMP,1,EX, , ,76E9,
UIMP,1,NUXY, , ,.3,
UIMP,1,ALPX, , ,33E-9 ,
UIMP,1,DENS, , ,2700,
! Make Material 2 "special" panel (note no density)
UIMP,2,EX, , ,62.1E9,
UIMP,2,NUXY, , ,.3,
UIMP,2,ALPX, , , 1E-9,
! Non-interlaced material
UIMP,3,EX,EY,EZ,ExxWC,EyyWC,10.3E9,
UIMP, 3,PRXY,PRYZ,PRXZ,vxWC,.3,.3,
UIMP,3,NUXY,NUYZ,NUXZ, , , ,
UIMP, 3, GXY,GYZ,GXZ,EssWC,3.195E9,3.195E9,
UIMP, 3, ALPX, ALPY, ALPZ,AlphxxWC,AlphyyWC,22.5E-6,
UIMP,3,DENS, , ,1800,

```
```

! Interlaced material
UIMP,4,EX,EY,EZ,ExxWI,EyyWI,10.3E9,
UIMP,4,PRXY,PRYZ,PRXZ,VxWI,.3,.3,
UIMP, 4,NUXY,NUYZ,NUXZ, , , ,
UIMP, 4, GXY,GYZ,GXZ, EssWI,3.195E9,3.195E9,
UIMP,4,ALPX,ALPY,ALPZ,AlphxxWI,AlphyyWI, 22.5E-6,
UIMP,4,DENS, , ,1800,
! 1 mm walls of +-YS90A prepreg, YS90A interlace . 45 vf
!UIMP,4,EX,EY,EZ,243.3E9,42E9,45.5E9,
!UIMP, 4,PRXY,PRYZ,PRXZ,.896,.3,.3,
!UIMP,4,NUXY,NUYZ,NUXZ, , , ,
!UIMP, 4, GXY,GYZ,GXZ,45.5E9,3.195E9,3.195E9,
!UIMP, 4, ALPX, ALPY, ALPZ,-.0862E-6,6.3E-6,19E-6,
!UIMP,4,DENS, , ,1800,
! Make Material 5 1mm walls of YS90A, 4 mm wide of . 45 vf YS80
UIMP,5,EX,EY,EZ,245.31E9,21.49E9,10.3E9,
UIMP, 5,PRXY,PRYZ,PRXZ,.710683,.3,.3,
UIMP,5,NUXY,NUYZ,NUXZ, , , ,
UIMP,5,GXY,GYZ,GXZ,45.5E9,3.195E9,3.195E9,
UIMP,5,ALPX,ALPY,ALPZ,-.0862E-6,6.3E-6,19E-6,
UIMP,5,DENS, , ,1800,
/COM REAL CONSTANTS FOR THIS ENVIRONMENT (same as before)
! top edge masses
R,1,TPEMASS,
! bottom corner masses
R,2,BTCRMASS,
! top corner masses
R,3,TPCRMASS,
! beams
R,4, , , , ,
! Make the wall panels (one layer thick aluminum originally)
R,5,PAN_THCK,,,,,
! This is the constant for the top panel, it's 5.5 mm thick
R,6,.0055,,r,'
! Ilz wall panels
R,7,PAN_THCK,,,,,
! Nilz wall panels
R,8,PAN_THCK,,,,,
/COM NOW WE CAN FIX THE STRUCTURAL BOUNDARY CONDITIONS
! This is the BC where all }8\mathrm{ support points are only constrained in Y
FLST,2,8,3,ORDE,8
FITEM,2,2
FITEM,2,10
FITEM,2,18
FITEM,2,26
FITEM,2,46
FITEM, 2,78
FITEM,2,82

```
```

FITEM, 2,90
!*
/GO
DK,P51X, ,0, ,1,UY, , , , , ,
! And the middle is constrained in X,Z,YROT directions.
FLST,2,1,3,ORDE,1
FITEM, 2,54
/GO
DK,P51X, ,0, ,1,UX,UZ,ROTY, , , ,
! Save as structural
PHYSICS,WRITE,struct
SAVE
FINISH
/COM PROCEED TO THERMAL SOLUTION
/SOLU
PHYSICS,READ,thermal
FINISH
/PREP7
! Select all elements
ESEL,ALL
! Unselect the aluminum beams and masses before solution
ESEL,S,TYPE,,1
!ESEL,A,TYPE, ,2
EDELE,ALL
! The lines have to be cleared separately
LSEL,ALL
LCLEAR,ALL
! And finally, the element types themselves must be eradicated
ETDEL,1
ETDEL,2
ESEL,ALL
FINISH
/SOLU
SOLVE
FINISH
! Show it to us in the post processor
/POST1
! First define graphics output variables
JPEG, QUAL, 75,
JPEG,ORIENT,HORIZ
JPEG,COLOR,2
JPEG,TMOD,1
/GFILE,600,
/TITLE,W%WALLNM (WALL) %C%CORENM (CORE) %THERM
/SHOW, JPEG
PLNSOL,TEMP, ,0,
PLNSOL,TEMP, ,0,
FINISH
/RENAME,file000,jpg,,W%WALLNM(WALL) %C%CORENM(CORE) %THERM, jpg,
! If the thermal distribution only is desired, uncomment the

```
```

! following end of file command. Otherwise the program proceeds
! to the structural solution.
!/eof
/COM NOW TO STRUCTURAL SOLUTION
RESUME ! Resume the model from the structural environment
/SOLU ! Transfer the results of the thermal model to structural
model
PHYSICS,READ,struct
ldread,temp,r,,r,rth
SOLVE
FINISH
! Show only the top layer
! This line is included because the GLAST problem is to determine
! the curvature of the grid and consequent tower misalignment
ESEL,S,MAT, ,2
! Show it to us in the post processor
/POST1
! First define graphics output variables
JPEG, QUAL, 75,
JPEG,ORIENT,HORIZ
JPEG,COLOR,2
JPEG,TMOD,1
/GFILE,600,
/TITLE,W%WALLNM (WALL) %C%CORENM(CORE) %STRUC
/SHOW,JPEG
PLNSOL,U,Y,0,1
PLNSOL,U,Y,0,1
ALLSEL,ALL
FINISH
/RENAME,file000,jpg, W%WALLNM(WALL) %C%CORENM(CORE) %STRUC,jpg,
/eof
! Reload thermal solution
PHYSIC,READ,thermal
/COM END OF LOOPS THAT ITERATE THROUGH LAYUPS
*ENDDO ! core loop
*ENDDO ! wall loop
/eof

```
```


[^0]:    * Ph.D. thesis, Stanford University, Stanford, CA, 94305

