"COMAND" ANALYSIS OF THE SHUTTLE ORBITER THERMAL PROTECTION SYSTEM TILES

A. D. Dobrowski* and J. Rowe**
Rockwell International
Downey, California

ABSTRACT

The Space Shuttle is protected thermally during atmospheric entry by approximately 31,000 silica tiles individually bonded to the substructure. The tile system must remain intact during all phases of the flight, sustaining loads imposed during ascent and descent in order to ensure a successful mission. The large quantities of complexly shaped tiles dictated the development of specialized, analytical approaches. This paper presents the computer program developed to analyze these tiles and automate the analysis of the Shuttle thermal protection system.

INTRODUCTION

The computer-organized manufacturing, analysis, and design (COMAND) program was developed to analyze the thousands of tiles that protect the Space Shuttle orbiter from the intense heat of atmospheric entry. COMAND uses a classical stress analysis approach, wherein the physical properties of a structure are represented by a math model consisting of a finite number of geometric node points, mass elements, and attachment elements to which loads are applied. The principles of general equilibrium, strain/displacement, and compatibility for three-dimensional bodies are used to calculate stresses and displacements of the structure. The physical parts of the tile system structure are silica tile, strain isolator pad, and the substructure. All three parts are modeled with COMAND.

Static loads are applied to the model by many methods: concentrated loads at node points, pressure loads on a surface, and acceleration loads at the model's center of mass. Shock, air, mechanical, friction, and substrate deflection loads can be generated by a single statement for each load type.

COMAND is a big step forward in automating the analysis of the Shuttle thermal protection system. Tiles with complicated shapes can be modeled easily, and the use of generic models lends itself to solutions for large numbers of tiles. Results are easily interpreted, and free-body diagrams can be obtained

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*Technical consultant
**Supervisor, TPS Penetrations Structural Analysis Group

directly from output. And solution time is extremely fast. Of utmost importance are the needs that led to the development of this program: low computer analysis cost, interactive capability, and the computer organizational management of vast amounts of data.

BACKGROUND

There are 30,759 tiles installed on the outer skin of the Shuttle orbiter. Each tile is bonded to a Nomex[1] (nylon) felt pad called a strain isolator pad (SIP), which in turn is bonded to the aluminum skin of the orbiter. Figures 1 through 3 typify the Shuttle thermal protection system (TPS). Figure 4 is a schematic of a typical 6- by 6-inch tile that shows the various parts of the installation: the silica tile, the SIP, the filler bar (a nylon felt material used as a thermal barrier), and the substructure. Figures 5 through 7 show typical geometries and complexly shaped tiles. As can be seen, the geometric shapes can be quite complicated; and the number of tiles (and, hence, the number of analyses) is extremely large. Variable SIP thicknesses and geometries plus variable tile densities add further complications to the Shuttle thermal protection system analysis.

The silica tiles are of two densities: 9 pcf (LI900) and 22 pcf (LI2200). They are extremely rigid, have low strength, and are attached to the aluminum substructure with a SIP that isolates the tile from the in-plane and

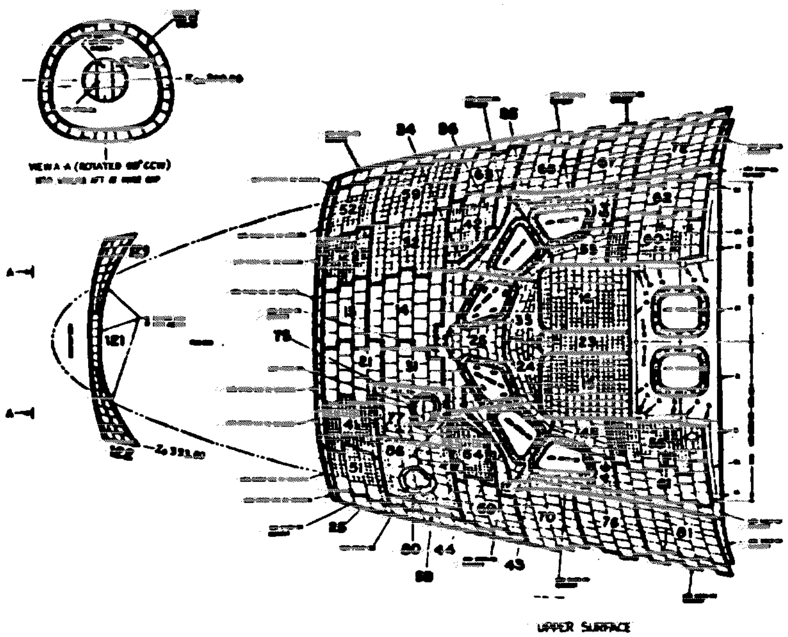

Figure 1. Upper Forward Fuselage Tiles

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[1] Trademark, E.I. du Pont de Nemours.

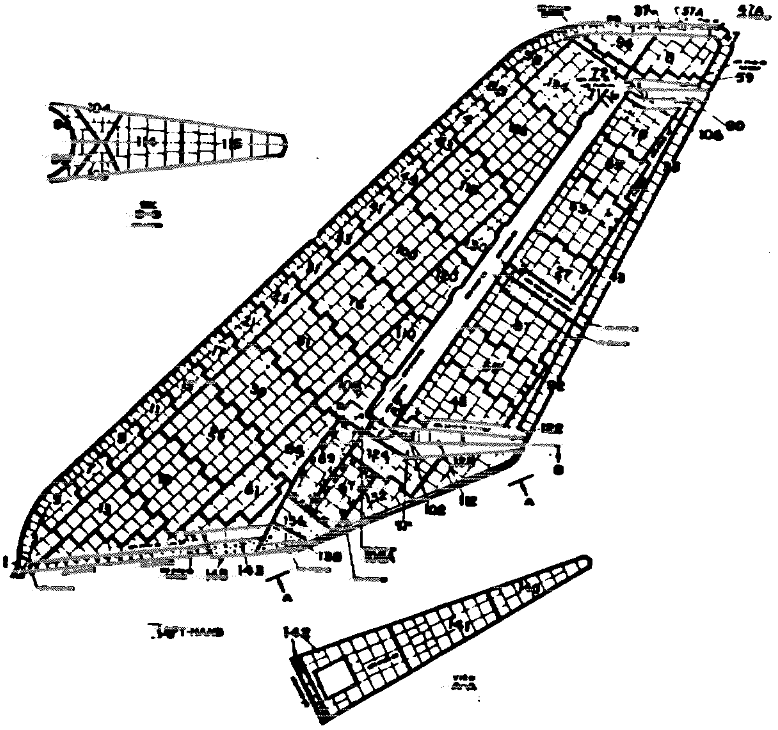

Figure 2. Vertical Stabilizer Tiles

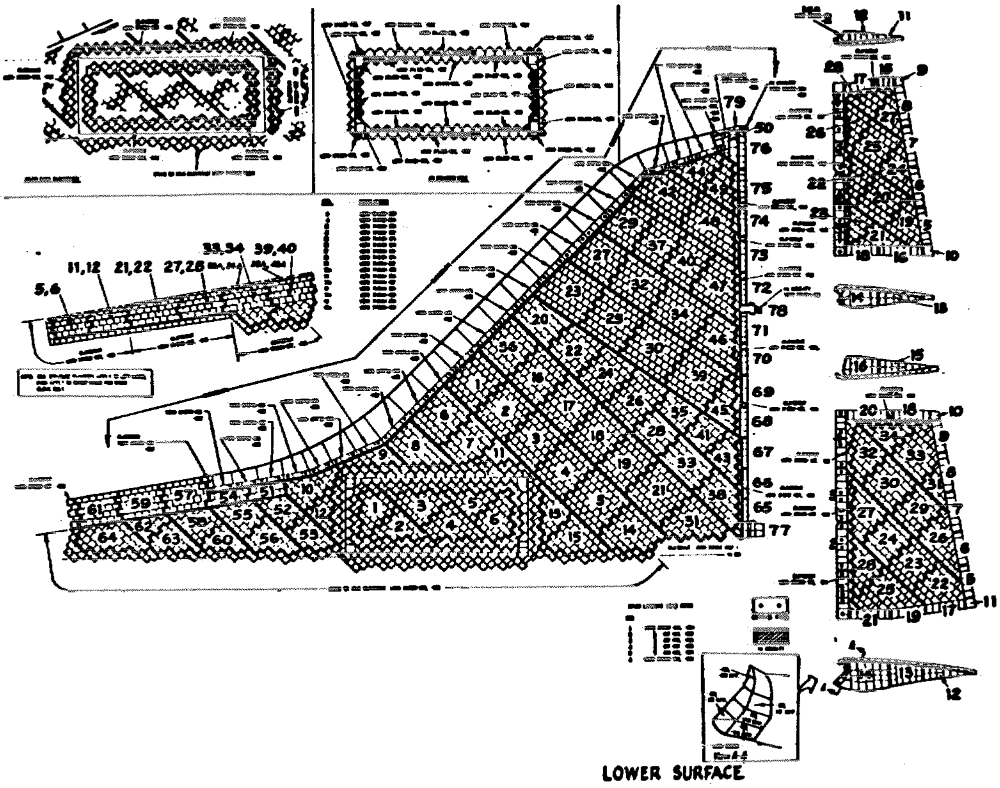

Figure 3. Wing Lower Surface Tiles

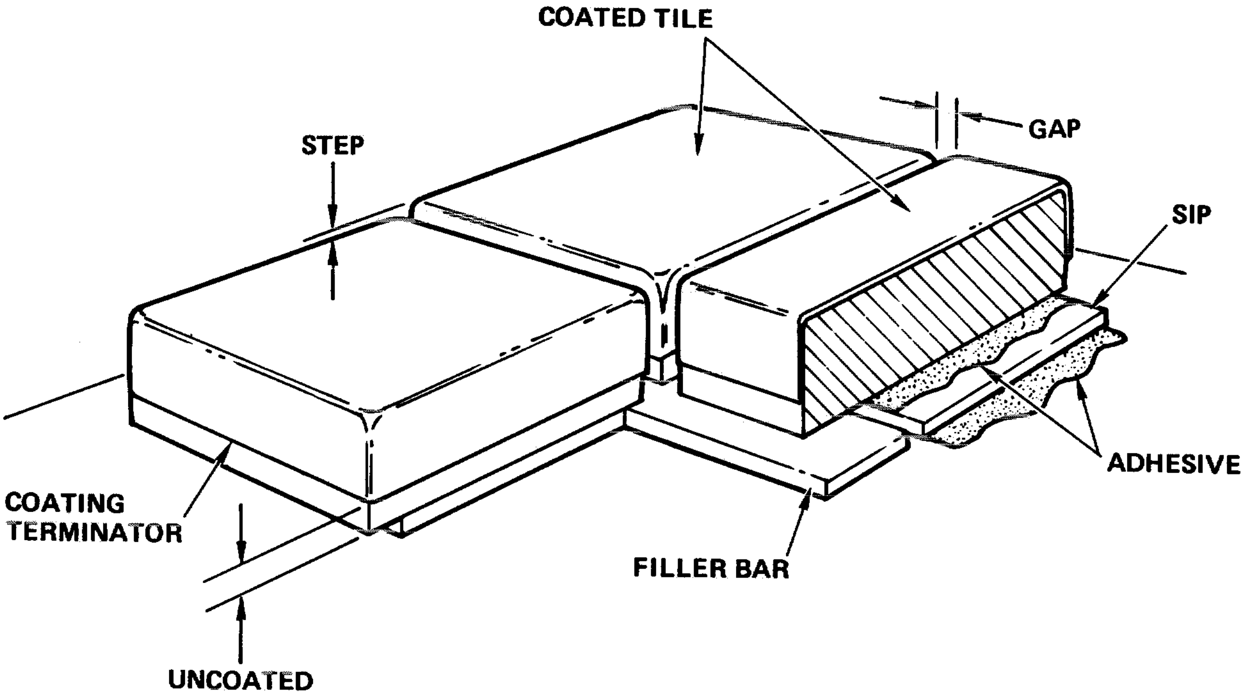

Figure 4. Typical Thermal Protection Tile Installation

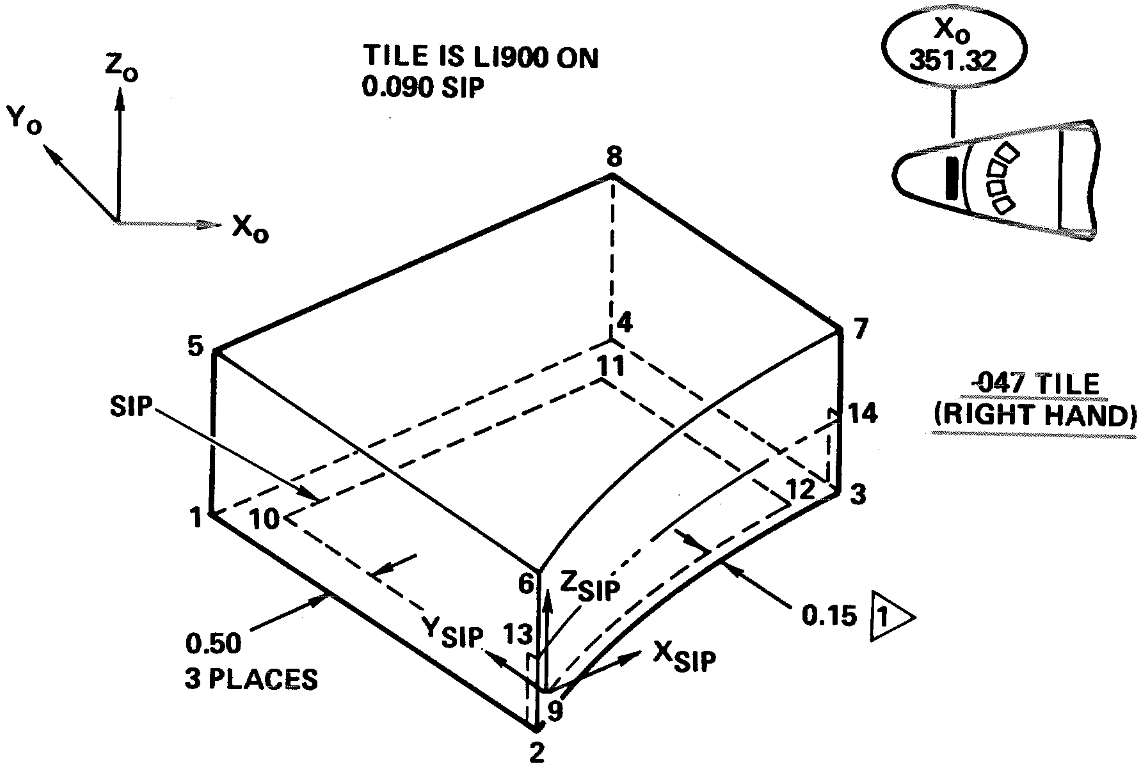

Figure 5. Forward RCS Thruster Tile

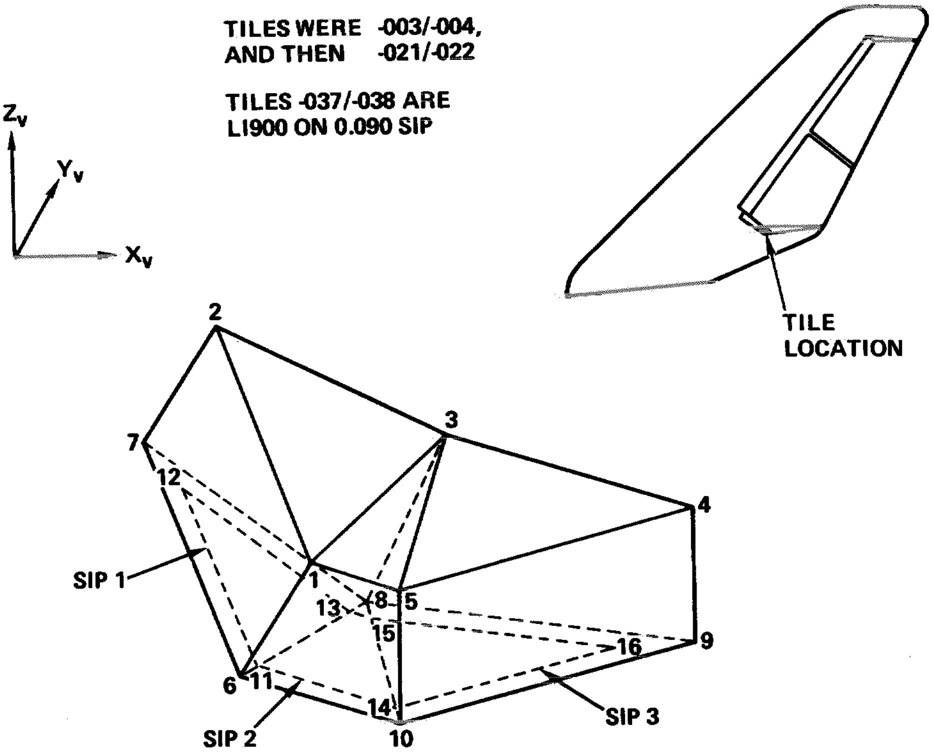

Figure 6. Vertical Stabilizer Tile

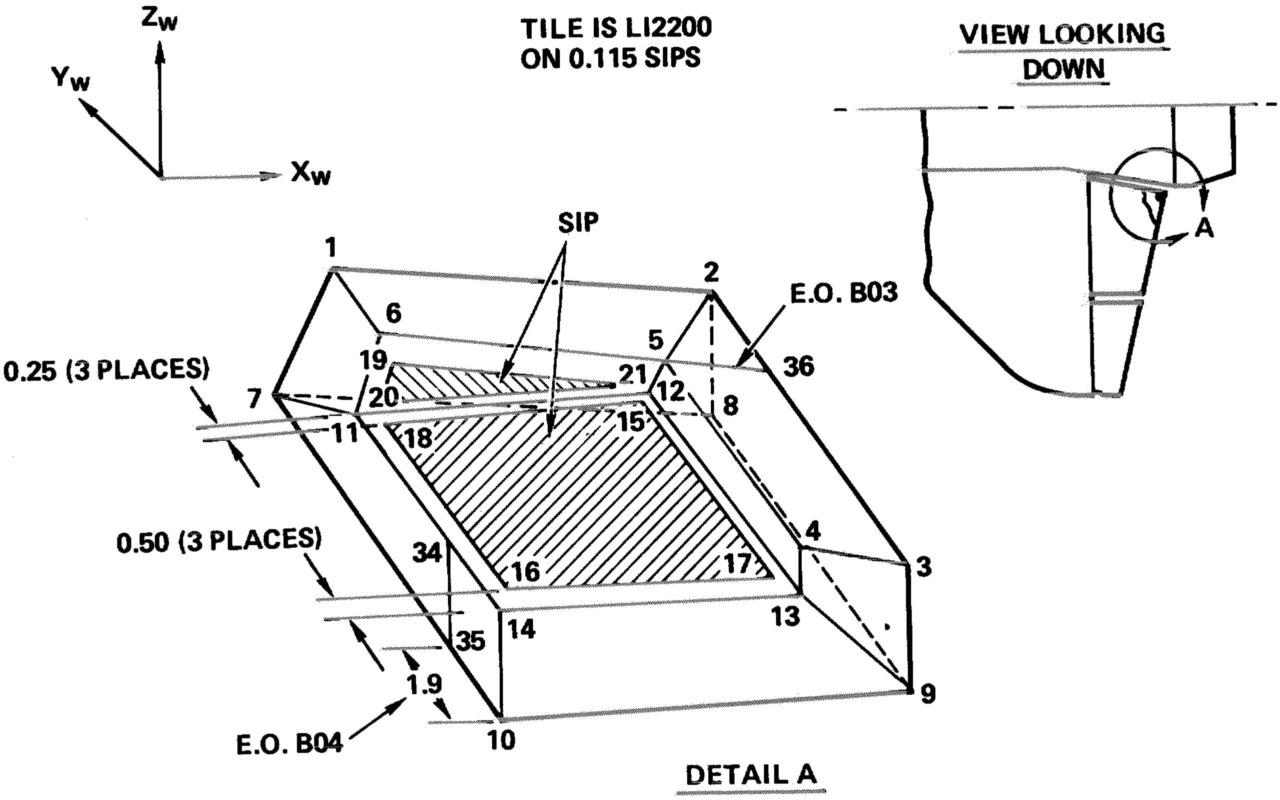

Figure 7. Inboard Elevon Aft Corner Tile

out-of-plane deflections of the aluminum skin. Early analysis of the tile installation system by two- and three-dimensional finite-element models (ASKA) showed the critical element of the attachment to be the tile at the SIP-to-tile interface. Testing of the tile/SIP assemblies confirmed the finite-element analysis.

Each tile is unique and must be evaluated for all the loads and environments to be encountered during a mission -- starting from engine ignition and passing through the environments of lift-off, ascent, orbit, descent, and landing.

The many loads and conditions that induce stresses on tiles can be summarized as follows:

1. Mismatch of the tile with the substrate caused by tile warpage during manufacturing, and imperfections of the substructure such as rivets, bulges, or doublers
2. Deflection of the substrate due to aerodynamic and acoustic loading, internal pressure, and thermal strains
3. Acoustic and vibration loads on the tile
4. Steady-state aerodynamic loads on the tile
5. Shock or unsteady-state aerodynamic loads on the tile
6. Mechanical contact loads caused by thermal barriers and gap fillers

All loads depend on time and tile location; in other words, the tile location and the mission trajectory define the spectrum of loads on tiles.

Each of the 30,759 tiles is evaluated for as many as nine mission time cuts and several load environments at each time cut. In addition, the requirements to locate the maximum shock loading on a tile add to the complexity of the problem. These analytical procedures would be monumental tasks if performed by hand calculations alone. The number of calculations could be reduced if a worst-on-worst combination of loads were assumed. However, the low strength characteristics of the tiles, 13 psi and 35 psi for the LI900 and LI2200 tiles respectively, dictate that more accuracy be obtained. Parametric plots in the form of curves could also be used to expedite analysis but they are useful primarily for standard-shaped tiles and do not lend themselves to automation.

Therefore, a computerized system was required. The normal finite-element approach was not feasible because of the numbers of elements required for each tile/SIP system and the time and costs associated with modeling and running a model. Furthermore, the normal finite-element approach would be difficult to automate for all orbiter tiles.

The large quantities of complexly shaped tiles dictated an interactive computer program (a computer-aided design environment) so that tiles could be modeled, viewed, and changed, if required. The analytical solution had to be fast because, with 30,759 tiles to be analyzed, even at a rate of only a few seconds per tile, computer time could run into days and costs could be prohibitive. The vast amount of data used for analysis (geometry, materials, and loads) dictated a data-base system to organize and store information. The computer program requirements were, therefore, as follows:

1. Organizational management of data
2. Fast computer analysis techniques
3. A computer-aided design environment

These requirements led to the development of COMAND.[1]

TILE MODELING

COMAND uses a classical stress analysis appraoch, wherein a critical cross section (tile-to-SIP interface) is determined; all loads are resolved on this section, and it is stressed. The physical properties of a tile are represented by a math model consisting of a finite number of geometric node points, mass elements, and attachment elements to which loads are applied.

Using a tile installation as shown in Figure 7 as a base, COMAND provides the necessary analytical methodology. The tile is modeled as solid elements with infinite stiffness. The substrate is also assumed to be rigid, and the SIP connecting the tile to the substrate is the flexible member of the structural system. The tile is assumed to be rigid and have six degrees of freedom (three in translation and three in rotation) at the tile center of gravity. The SIP's are characterized by bar elements, and a matrix solution is used to solve for stresses and displacements.

The geometric node point, a point in three-dimensional space, forms the basic framework for the tile structural model. All other parts of the model are referenced either directly or indirectly to the node point. The geometric node point is defined by using the NODE data card. The implicitly defined, basic coordinate system is rectangular. All local coordinate systems defined in the modeling procedure are rectangular and right-handed.

The node point itself has no properties or degrees of freedom but is used as a basic framework for the structural model. Once the coordinates of a node point are defined, that node point can be used to define other node points or elements. The coordinates of a node point also can be redefined during the modeling process and then reused. Node points can be defined by plane-line intersections, line vectors, normal vectors, perpendicular vectors, and other interactive computer-aided design commands. This interactive process can be done in a batch mode with cards or on a CRT terminal.

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[1] Although not discussed in this paper, computer-aided manufacturing is the next step, once a tile is described by a computer-aided design program.

Elements are defined on connection cards that identify the node points to which the element is connected. There are two basic elements in COMAND: the mass element and the pad element. The mass elements are defined with a BLOCK, WEDGE, TETRA, and FACE card (Figure 8). Each element, when defined, adds only mass to the tile model and has no structural capabilities. The mass of the model is acted upon directly by inertia loads only.

The pad element, defined with an SIP card or a FILLER-BAR card, includes extension, torsion, bending in two perpendicular planes, and the associated shear stiffnesses. These cards define the SIP attachment cross section and the mechanical properties of the SIP and filler bar.

Material property definition cards are used to define the properties of only the pad elements. The MATERIAL card can be used to define either a linear or nonlinear material property.

Two solution procedures are used to calculate stresses and tile displacements. The first solution procedure is evoked by the STRESS data card. It is a simple static matrix solution.[1] Although this solution works well for linear SIP, its inability to handle nonlinear SIP materials and filler-bar material characteristics soon became apparent and an additional capability was developed.

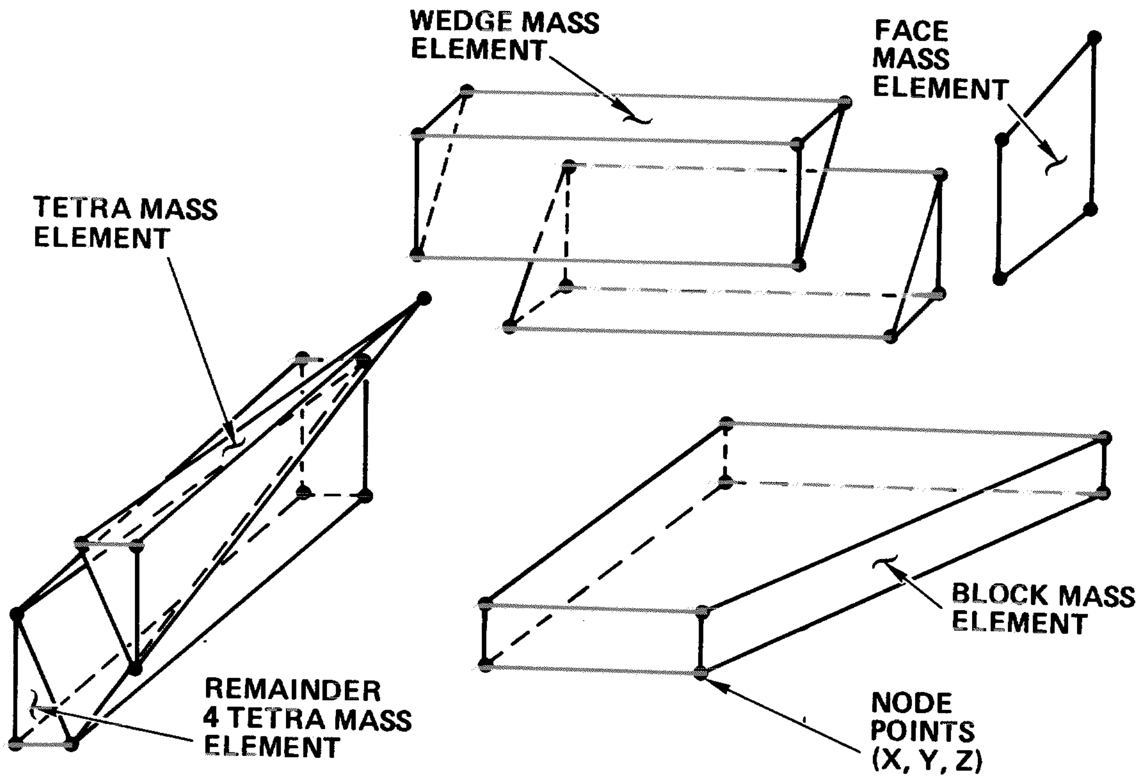

Figure 8. Tile Modeling

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[1] Przemieniecki, J. S. Theory of Matrix Structural Analysis. McGraw-Hill, Inc. (1968).

The second solution procedure, a nonlinear analysis developed at NASA's Langley Research Center, is evoked by the NL-STRESS data card.[1] The tile again is assumed to be rigid and have six degrees of freedom, and the SIP is characterized by a linear or nonlinear stress/strain curve. A Newton-iteration scheme is used to determine stresses and displacements. (See Figure 9 for SIP modeling.) This solution procedure[2] solves the interactions of the tile-to-SIP system accurately. It solves nonlinear SIP behavior, takes into account the inability of the filler bar to take tension loads, and calculates stresses in the SIP caused by substrate deformations.

LOAD APPLICATION

Static loads are applied to the model by many methods: concentrated loads at node points, pressure loads on a surface, acceleration loads at the center of mass of the model, and substrate deflections. Shock, air, mechanical, drag, and substrate deformation loads can be generated by a single statement for each load type. The FORCE and MOMENT cards are used to define a static load applied to a geometric node point.

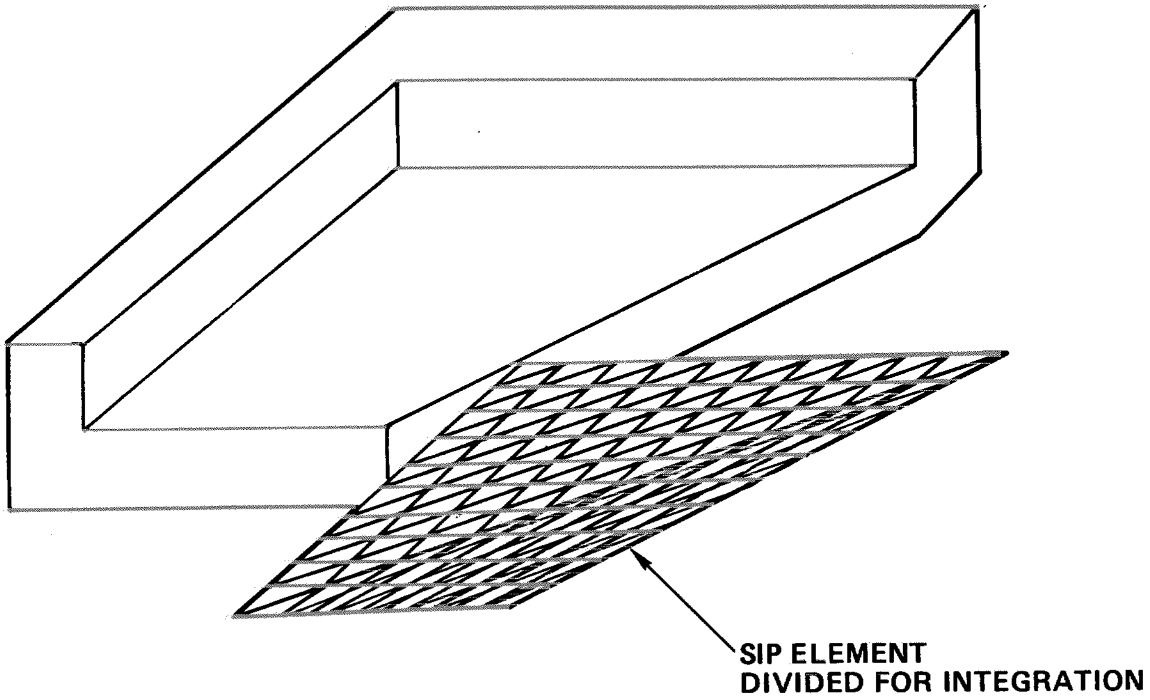

Figure 9. SIP Modeling

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[1] Housner, Jerrold M., and Ramon Garcia. Nonlinear Static TPS Analysis. NASA TM81785 (March 1980).

[2] The programming and coding of this procedure into COMAND were done by Dr. Gary Giles and Maria Valles of NASA.

Pressure loads on triangular surfaces are defined with a PRESSURE card. The magnitude and direction of the load are automatically computed from the pressure and the coordinates of the connected node points. The GLOAD and the VIBRO-ACCL cards are used to specify an inertia load by providing the components of the inertia vector in the global coordinate system. The inertia load is obtained from the inertia vector and the mass of the tile.

The THERMO-BAR card is used to specify a line load. The magnitude and direction of the load are automatically computed from the line load and the coordinates of the connected node points.

The AIRLOAD and the SHOCK cards are used to specify aerodynamic loading on the model. The aerodynamic pressures on the tile are generated automatically. These cards are used in conjunction with the NPMATRIX and the NSMATRIX, which define the pressure model.

The SUBST-DEFL card is used to specify a variety of substrate deformations (cylindrical, single cosine, double cosine, spherical, etc.) because imposed displacements of the substrate can generate stresses in the tile-to-SIP interface.

Figure 10 illustrates thermal protection system load modeling.

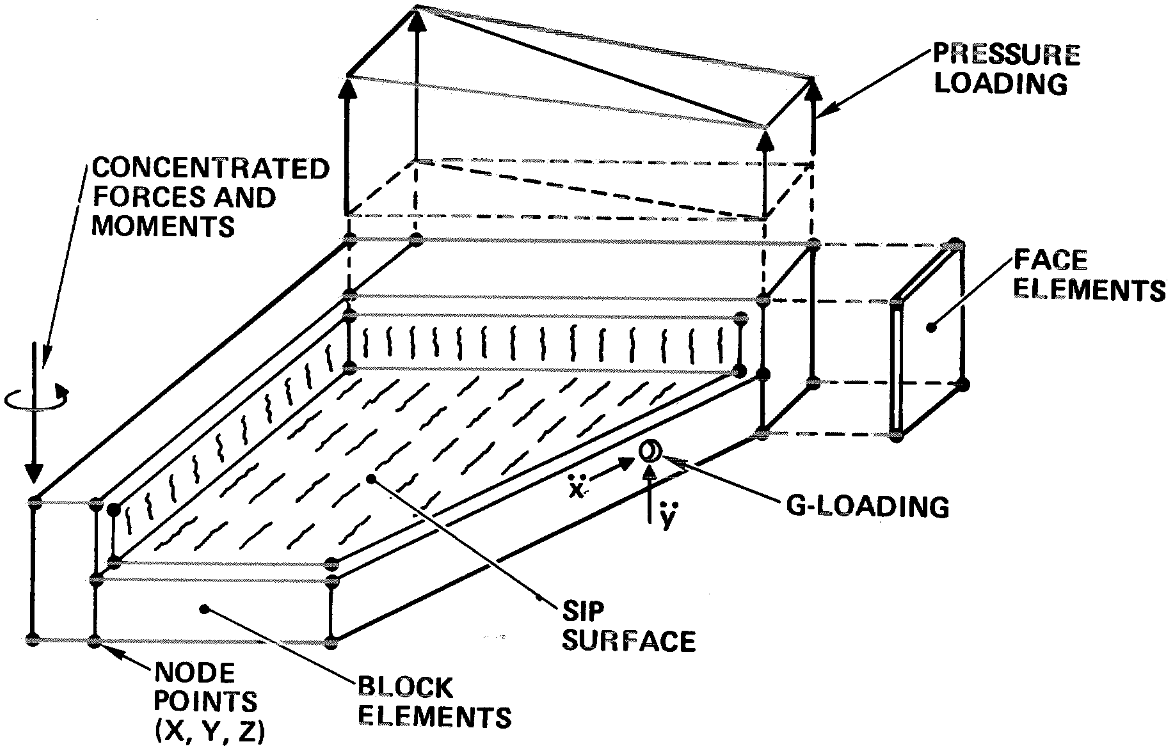


Figure 10. TPS Modeling

APPLICATION

THERMAL PROTECTION TILES

To illustrate the application of the COMAND program, the tile shown in Figure 5 will be evaluated. Corner points of the tile are obtained from the Master Dimension Group at Rockwell and the tile is modeled. Node Points 1, 2, 3, 4, 5, 6, 7, and 8 define the corner points of the tile and are used to develop the mass of the tile. Node Points 9, 10, 11, and 12 define the size of the SIP footprint. This tile is subjected to the following loads:

1. Out-of-plane deflections
2. Mechanical loads (gap fillers)
3. Aerodynamic shock pressures and aerodynamic load
4. Vent lag pressure
5. Vibroacoustic load

Figures 11 through 16 show free bodies of the applied loads and the resultant stresses.

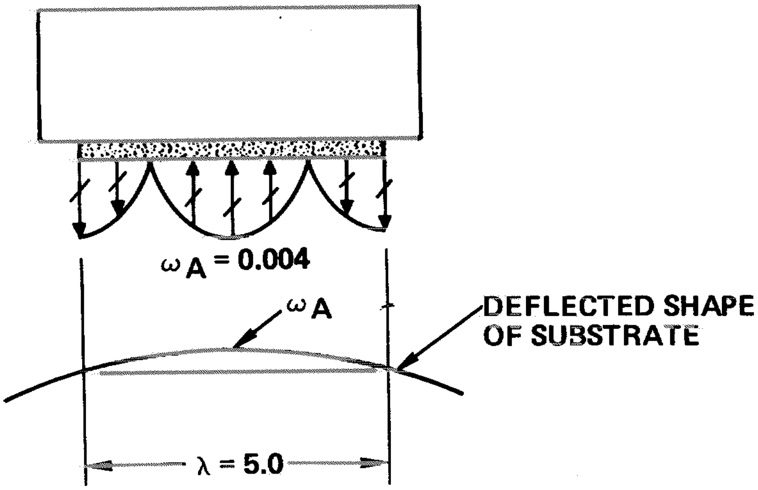


Figure 11. Tile Free Body Caused by Substrate Deflection

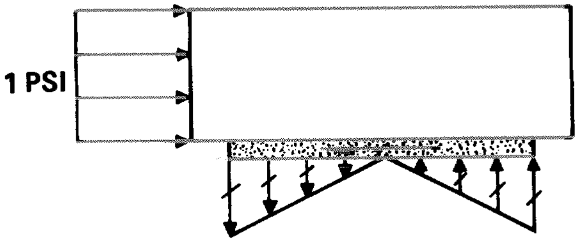


Figure 12. Tile Free Body Caused by Gap-Filler Mechanical Load

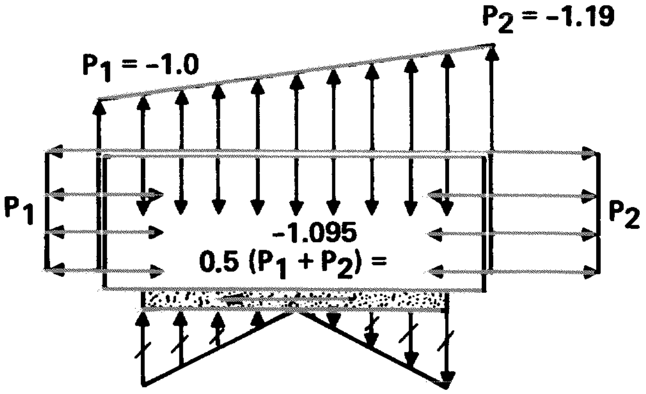


Figure 13. Tile Free Body Caused by Aerodynamic Load

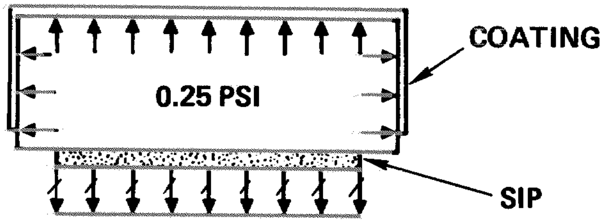


Figure 14. Tile Free Body Caused by Vent Lag

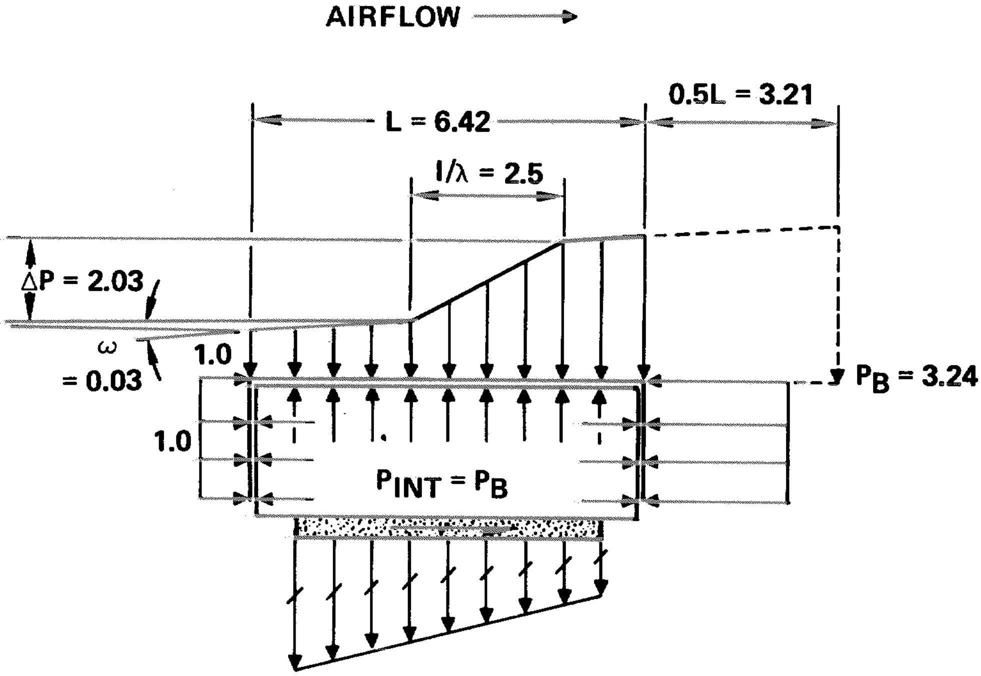


Figure 15. Tile Free Body Caused by Aerodynamic Shock

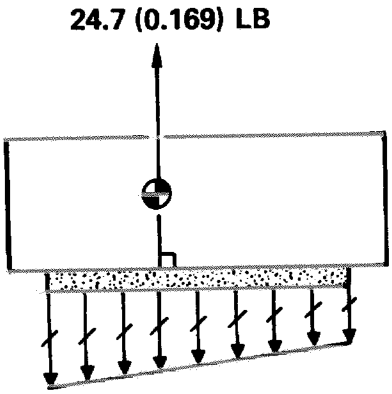


Figure 16. Tile Free Body Caused by Vibroacoustic Acceleration

The program outputs the tile/SIP information regarding physical properties such as tile weight and center-of-gravity location, and SIP center-of-gravity location, area, and moments of inertia. COMAND also develops the stress in the SIP at the SIP corner points and defines the rigid body movement of the tile and the deflections at the tile node points. SIP stresses for the tile are defined in Table 1.

If a free-body diagram of the tile is desired, the resulting loads imposed on the tile are defined at the tile center of gravity. To illustrate the nonlinear analytical capability of the program, a SIP stress-versus-deflection curve (such as the one in Figure 17) can be applied to the problem.

Results of the nonlinear analysis and a comparison with the initial linear analysis are presented in Table 2.

OTHER USES

Although the COMAND program was developed for analyzing the Space Shuttle tile installations, it can be used for other fields of structural engineering, primarily where load-versus-deflection structural characteristics exist -- for example, the bolted flange connection of a water line subjected to axial loads, moments, transverse shear, and bolt preloads. The pipe flanges are the rigid members of the system, and the bolts and flange compression areas are simulated as the SIP's. Bolt preloading is defined by the load/deflection curve of the bolt. Figure 18 illustrates a typical flange joint; the model representation of the flange and bolts is shown in Figure 19.

Assumptions and resulting calculations for the preloaded flanged coupling are presented in Figures 20 and 21. The eight preloaded bolts and the compression flange are all assumed to be SIP's; therefore, their load versus deflection must be defined in curves. Results of the solution are presented in Figures 22 and 23.

Table 1. SIP Stresses

Load Condition	Stress at Node No.			
	9	10	11	12
Mismatch	4.44	4.44	4.44	4.44
Out-of-plane δ	0.69	0.71	0.61	0.64
Vibroacoustic acceleration	0.20	0.16	0.48	0.52
Vibroacoustic δ	0.06	0.06	0.06	0.06
Mechanical	0.93	-1.14	-0.38	1.09
Overpressure	-	-	-	-
Pressure lag	0.40	0.42	0.40	0.38
Aerodynamic shock	4.72	2.75	3.44	4.55
Aerodynamic load	0.14	0.07	0.01	0.02
Σ Stress				
Ascent without shock	6.86	5.86	6.00	7.15
Ascent with shock	11.18	8.32	8.89	11.10

Table 2. Nonlinear Versus Linear Analysis

Load No.	Load Condition	Nonlinear Stress Node 9	Linear Stress Node 9
1	Mismatch	4.44	4.44
2	Out-of-plane δ	0.14	0.69
3	Mechanical	0.93	0.93
4	Pressure lag	0.40	0.40
5	Aerodynamic shock	5.38	4.72
1+2+3+4+5	Total	11.29	11.18
1,2,3,4,5	Nonlinear total	10.79	

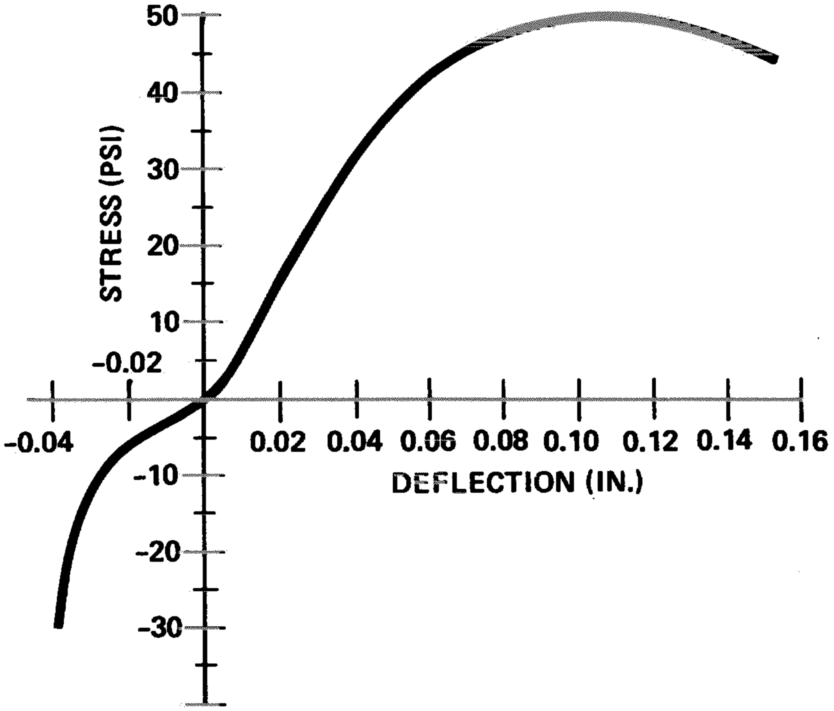
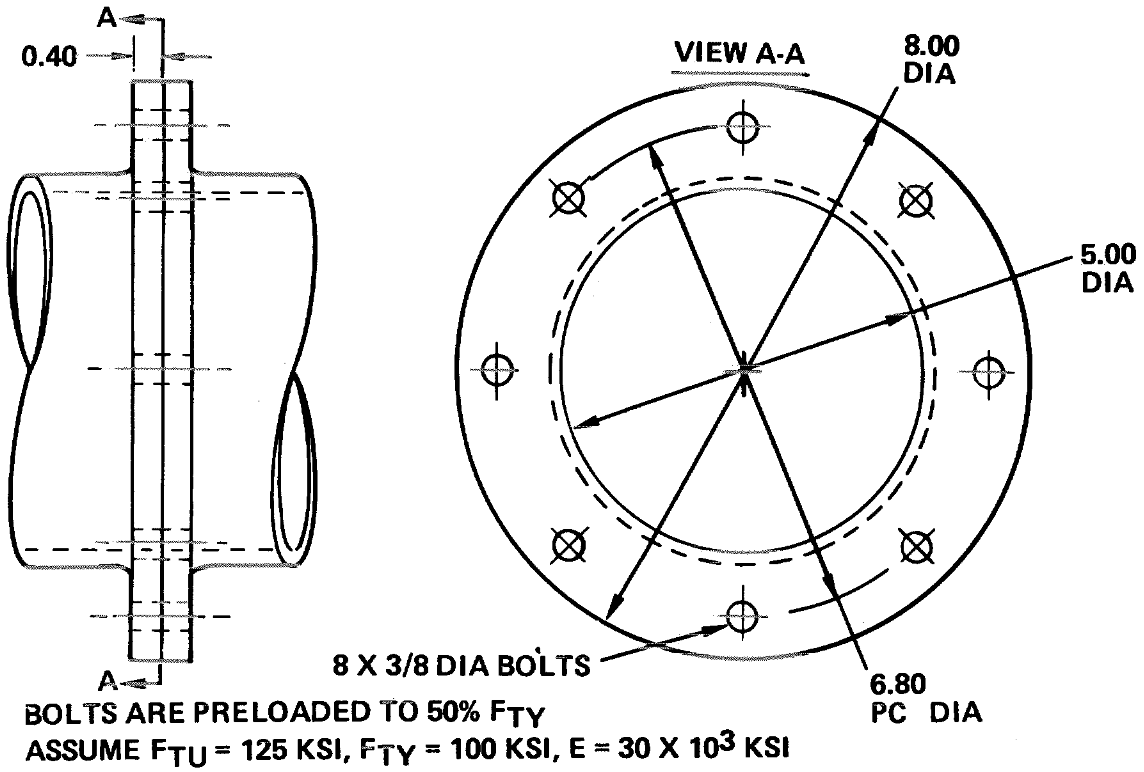
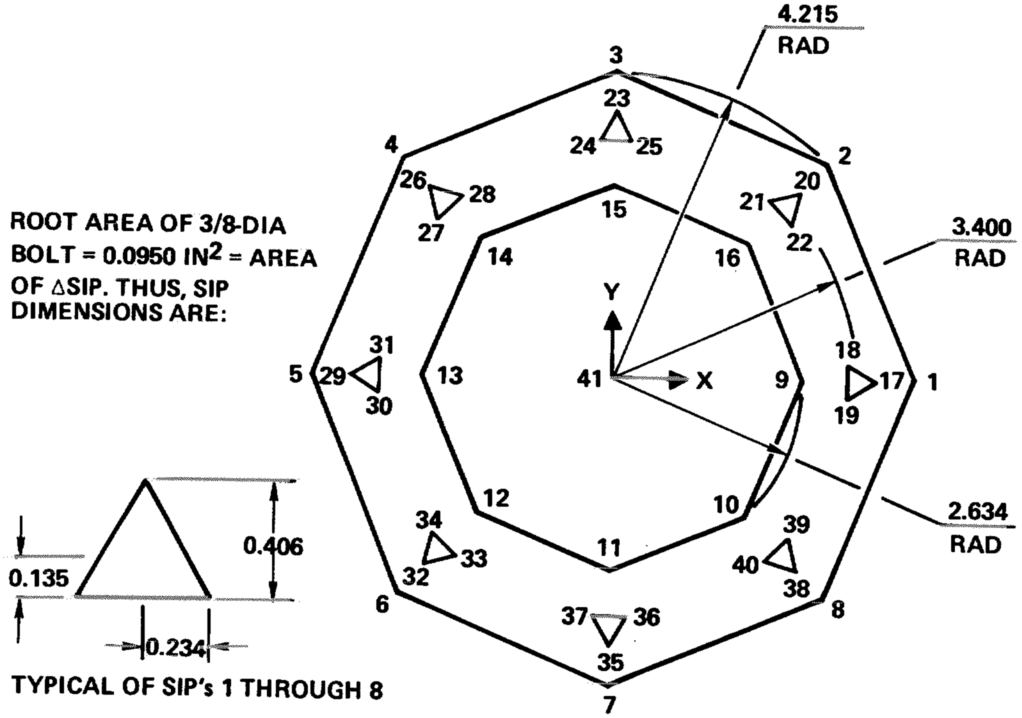


Figure 17. SIP Stress-Versus-Deflection Curve for 0.090 SIP



BOLTS ARE PRELOADED TO 50% F_{TY}
ASSUME F_{TU} = 125 KSI, F_{TY} = 100 KSI, E = 30 X 10^3 KSI

Figure 18. COMAND Analysis of Preloaded Flanged Coupling



SIP 9 IS FLANGE (BOLT HOLES ARE IGNORED -- NEGLIGIBLE)

Figure 19. Analysis of Idealized Bolts and Flange of Preloaded Coupling

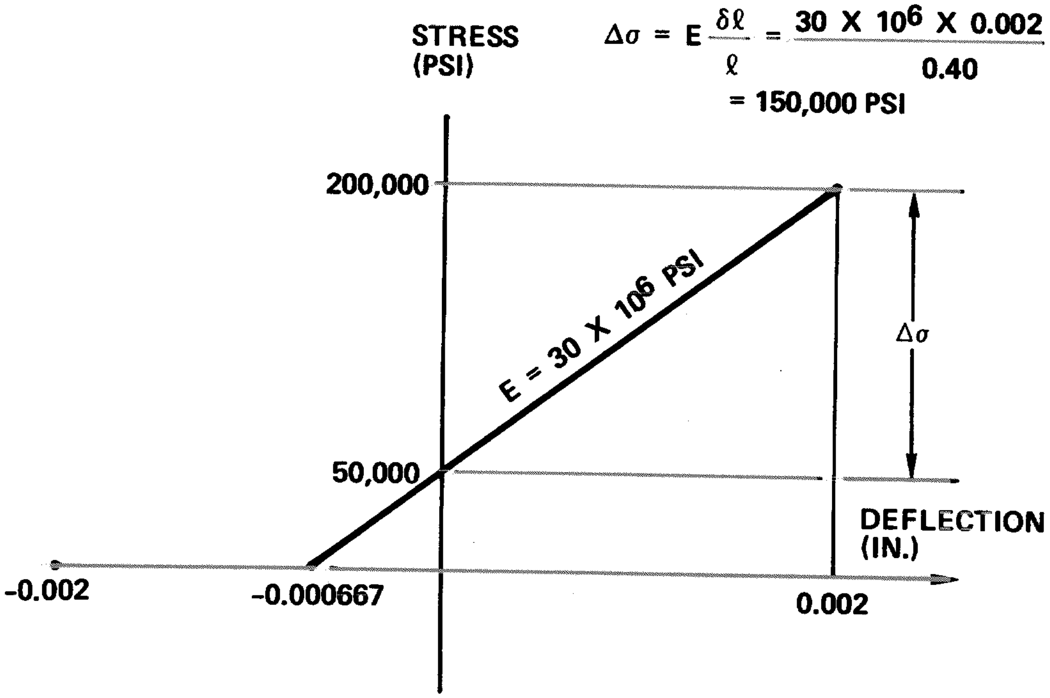


Figure 20. Stress/Deflection Curve of Bolts

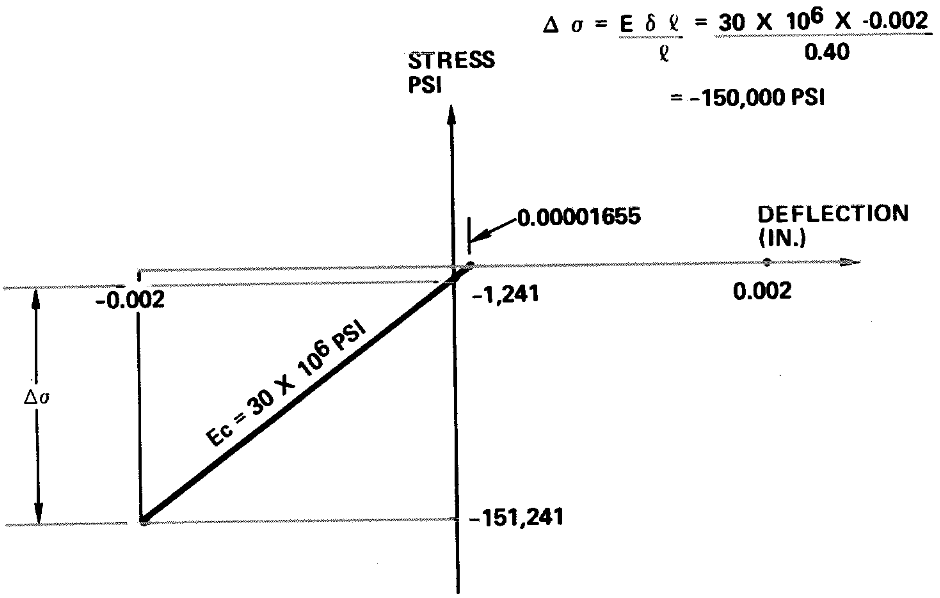


Figure 21. Stress/Deflection Curve of Flanges

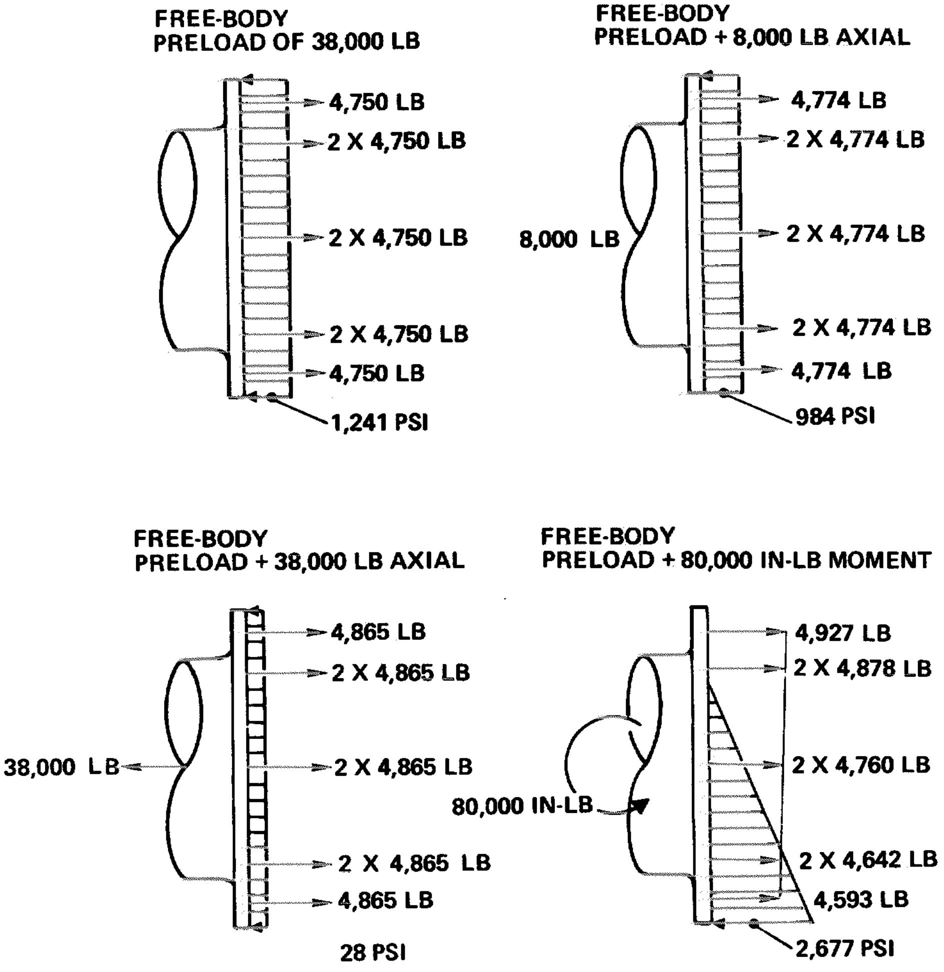


Figure 22. Analysis of Preloaded Flanged Coupling

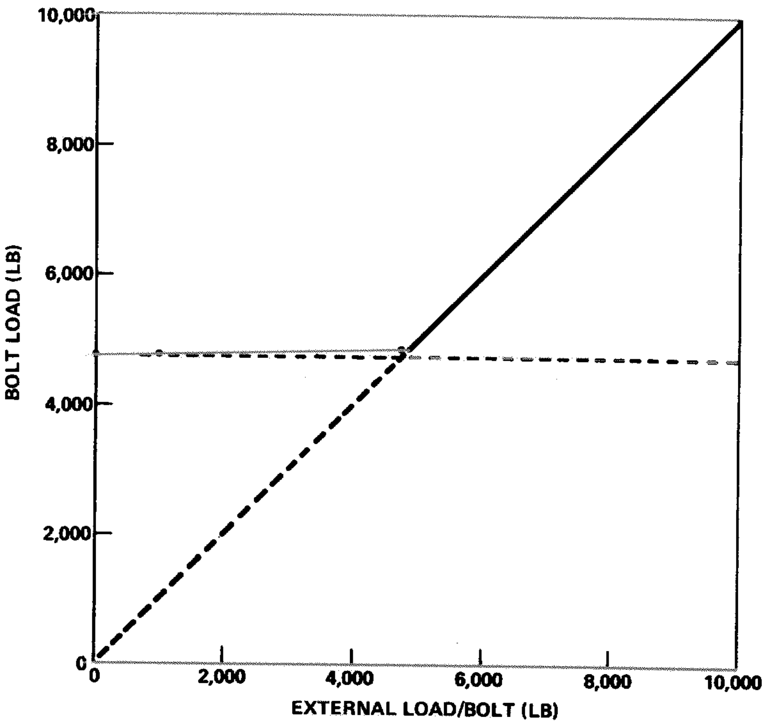


Figure 23. Plot of Preloaded Flanged Coupling

SUMMARY

COMAND is a big step forward in automating the analysis of the Shuttle thermal protection system. It does not solve unnecessary parts of the structure in order to resolve loads for the critical section. Therefore, it is a fast and inexpensive solution. The models are concise and relatively few cards are used. Thousands of models can be stored in a data base, representing the entire vehicle. Loads can be mapped to orbiter coordinates so that the entire tile system is stressed by the computer technology.

ACKNOWLEDGEMENTS

The authors wish to thank the Thermal Protection System Penetrations Structural Analysis Group at Rockwell for their constructive criticism during the development of this computer system and for the analysis and examples furnished by D. B. Moore that were used in this paper. Thanks also to Dr. Gary Giles and Maria Valles of NASA's Langley Research Center for programming and inserting the NASA Langley stress solution into COMAND.