STRESSES IN ACOUSTICALLY EXCITED PANELS AND SHUTTLE INSULATION TILES

FINAL REPORT

July 1977

GRUMMAN

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By

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July 1977

Prepared by

Grumman Aerospace Corporation
Bethpage, N.Y. 11714

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FOREWORD

The work reported herein was performed by the Grumman Aerospace Corporation under the NASA/Langley Master Agreement and Contract No. NAS 1-10635 for the Development and Implementation of Space Shuttle Structural Dynamics Modeling Technology. The Work Statement of Task Order No. 17-Modification No. 4, "Development of an Analytical Program to Analyze Reusable Surface Insulation for Shuttle," authorized and specified the items to be performed in this study. This report, which is the third and final report in a series, covers Items J through K of the subject Task Order, for which the period of performance was August 1975 through November 1976. Items A through E were reported upon in NASA CR-132553, September 1974 and items F through H were reported upon in NASA CR-144958, August 1975.

The overall supervision of programs under the Master Agreement was provided by Mr. E. F. Baird, Master Agreement Program Manager. The Task Order No. 17 Project Manager was Dr. I. U. Ojalvo.

ACKNOWLEDGEMENT

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CONVERSION FACTORS

Inches to Centimeters	Multiply by 2.54
PSI to Paschals (N/M^2)	Multiply by 6.894757×10^3
PSI^2 to Pascals ^{2} $(N/M^2)^2$	Multiply by $(6.894757 \times 10^3)^2$

ABSTRACT

This report describes improvements to the RESIST and ARREST computer programs, previously developed for determining the normalized modal and dynamic stress response of shuttle insulation tiles. The new versions of RESIST and ARREST can accommodate a thin layer of bond material on either side of the strain isolator and high temperature coating on the sides, as well as on the top, of the RSI tiles.

Natural vibration and acoustic response results are presented for a 36x18-inch panel with 18 6x6-inch tiles of 1.0, 1.6 and 2.3 inch thicknesses. Computed results for an untiled panel are compared with experiments performed at the NASA/Langley Research Center. Natural frequency and acoustic response comparisons are also given for independent analyses performed upon tiled and untiled panels. The results indicate the general applicability of the computer programs developed for use as shuttle design and analysis tools.

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Section 1

INTRODUCTION

This report describes extensions to the structural idealization of previously developed computer programs for analyzing the space shuttle thermal protection system (TPS). Results obtained from the use of these programs, for typical shuttle panels, are presented and comparisons are made with independently performed analyses and tests.

The previously developed computer programs are titled: REusable Surface Insulation STresses (RESIST) and Acoustic Response of REusable Shuttle Tiles (ARREST). Both are described in detail in References 1 through 4. Extensions to the idealization, performed in the present work phase, involve improvements to the finite element modeling of the shuttle reusable surface insulation (RSI) tiles. The modifications involve the inclusion of a high temperature coating partway down the sides of each tile, in addition to the coating on the top of the tiles, and the inclusion of thin layers on either side of the strain isolator to represent the bond material. Details of these modifications are presented in Section 2 and Appendix A, which is a Users Manual for the latest version of RESIST. The ARREST program remains as detailed in Ref 3.

Natural vibration results based upon the most recent version of RESIST are presented for a range of RSI tile thicknesses, including 0 (no tiles), 1.0, 1.6 and 2.3 inches, affixed to a stringer-stiffened structural panel containing 18 6x6-inch tiles. These results are compared in Subsection 3.2 to tests conducted by Rucker and Mixson at the NASA/Langley Research Center (Ref 5) and independent analyses, performed by Dowell, which are included in Reference 6.

Detailed tile stress results obtained with the ARREST program are presented for an assumed loading spectrum associated with an aft section of the shuttle orbiter fuselage at launch. These results are compared in Subsection 3.4, with an analysis based upon time simulation conducted by Vaicaitis (Ref 7).

RMS strain comparisons, for an untiled panel, are also presented. These are for results obtained from the ARREST program and random acoustic tests conducted at Langley in their Thermal Acoustic Fatigue Apparatus (TAFA). Details of these comparisons are contained in Subsection 3.5.

Section 2

COMPUTER PROGRAM MODIFICATIONS

A number of changes to the original version of the RESIST program, as described in References 2 and 4, were made to improve its usefulness. Some of these changes were described in NASA CR 144958, (Ref 3). Further updates to the program, which refine the detailed structural idealization of the tile, are discussed here. These latest changes have been incorporated in the February 1976 version of the program described in Appendix A of this report.

2.1 TILE COATING

A high-temperature coating material is used on top of each RSI tile. The purpose of this coating is to minimize the amount of moisture absorbed by the tiles. Since the coating is susceptible to cracking, its accurate structural representation and stress levels are of interest. Although this coating was included on the top surface in the original idealization of the tiles, it was not known that the coating extended part-way down the sides of each tile. To correct this situation, the program was extended by including a series of temperature-dependent membrane elements on the sides of each tile. The coating elements may progress down the sides by any amount between zero and the entire tile thickness - in equal steps. The step sizes correspond to the through-the-thickness dimensions of the three-dimensional finite elements used to idealize the tiles themselves.

2.2 BOND LAYERS

The strain isolator pad (SIP) of each tile is bonded to both the RSI tile and the primary structure. The adhesive material used is an RTV bond layer with stress levels that must be known to check its suitability. These bond layers have now been idealized as thin quadrilateral membrane elements with temperature-dependent properties. They share common nodes with either the top or bottom surface of the three-dimensional SIP element nodes. This idealization permits the program user to treat the bond layers on either side of the SIP separately and to obtain their in-plane direct and shear stresses. Because the layers are extremely thin, the out-of-plane direct and shear stresses in the bond may be assumed identical to those in the corresponding three-dimensional SIP elements.

Section 3

NUMERICAL APPLICATIONS

Finite element results were obtained for an 18 x 54-inch stringer-stiffened panel, with and without RSI tiles, undergoing testing at the NASA Langley Research Center. Three different tile thicknesses were considered. Modal and acoustic response results were then obtained for an assumed loading spectrum associated with an aft section of the shuttle orbiter fuselage at launch. Natural frequency comparisons were made between those obtained with the RESIST finite element program and a Rayleigh-Ritz procedure developed by Dowell (Ref 6). Finite element modal and broad-band acoustic response results were also compared, for the untiled panel, with shaker (Ref 5) and narrow-band acoustic tests conducted by Rucker and Mixson at the Langley Research Center, and simulation analyses performed by Vaicaitis (Ref 7).

3.1 STRUCTURAL CONFIGURATION

The RSI-tiled panel of Figure 3-1 was analyzed by the RESIST program. There are 18 6x6-inch tiles between supports, all of which are either 0, 1.0, 1.6 or 2.3 inches thick. There is a 0.01-inch thick coating over the top of each tile which also extends part-way down the sides of each tile. The strain isolator thickness is 0.16 inches. Nine-inch metal extensions, partially covered with tiles which extend over the edge of the supports, were assumed to act as rigid bodies with rotatory inertia properties comparable to the interior (36-inch) section of panel. The RESIST program overall idealization of the panel is shown in Figure 3-2 and the detailed finite element idealization of a typical tile is shown in Figure 3-3.

3.2 NATURAL VIBRATIONS

The method used to obtain modal solutions is an adaptation of an engineering technique proposed by Newman and Goldberg for the static analysis of an ablative heat shield (Ref 8). The iteration scheme is based on the significant difference between the elastic properties of the TPS and primary substructure. The work by Ojalvo, Austin and Levy (Ref 1) extends the original concept through consideration of inertia,

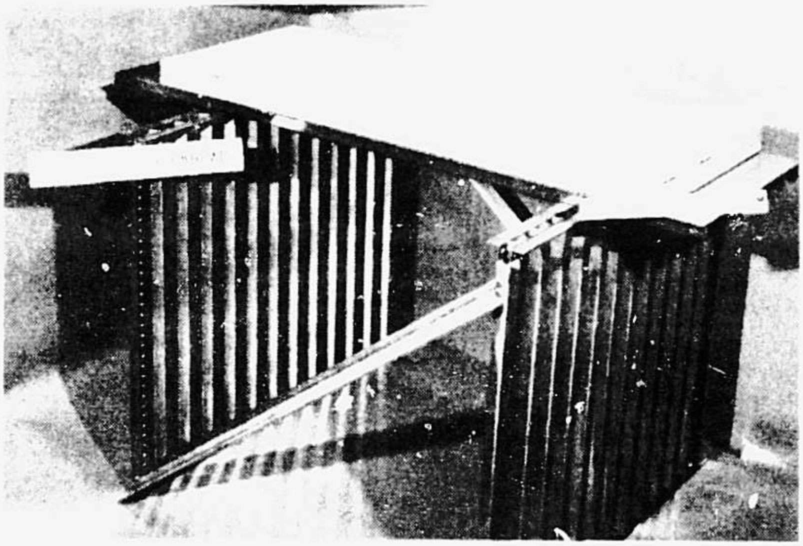

Figure 3-1 Langley Panel with 24 6x6x2.3-inch RSI Tiles and Simulated Bulkhead Supports Spaced 36 Inches Apart (There are 18 tiles between supports)

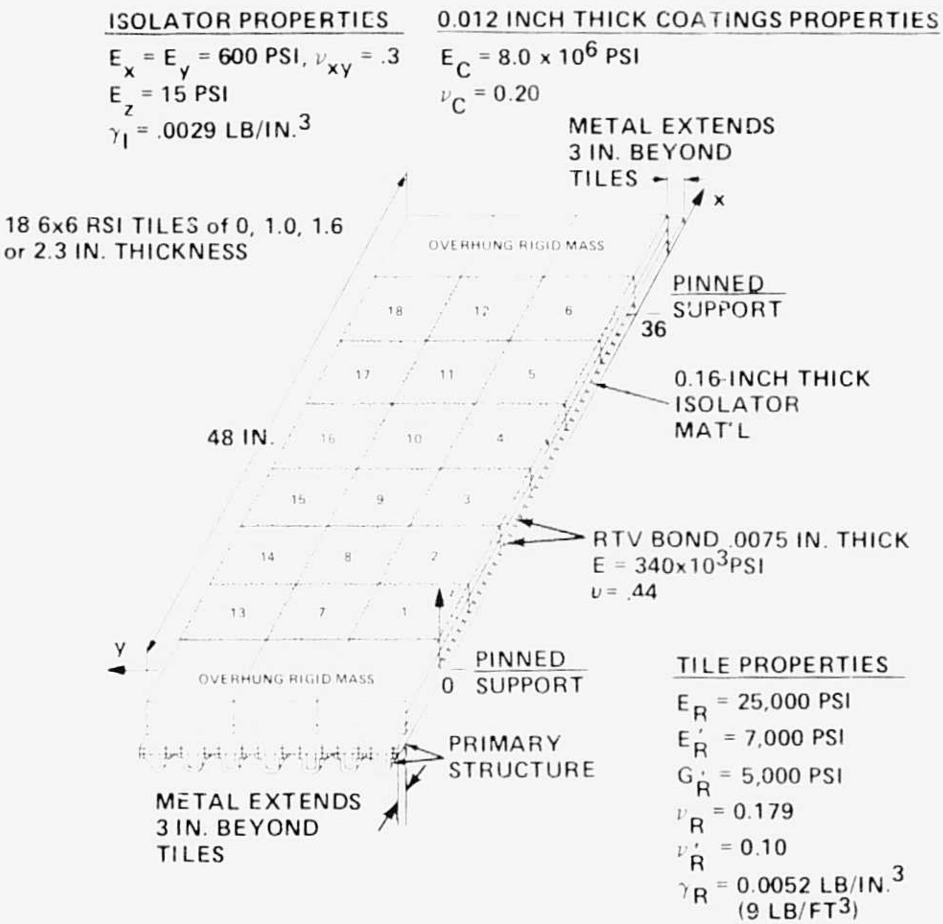

Figure 3-2 Idealized Panel with 18 Flexible 6x6-inch Tiles Over a 36-inch Span Between Supports

as well as stiffness, effects. A derivation for the conditions under which the general procedure will converge is presented in References 9 and 1.

The basis for the method is that the TPS is nonstructural but its stress levels, which are critical for integrity of the vehicle TPS, must be computed. Thus, it becomes possible to neglect the stiffness of the TPS initially, but not its mass, to determine approximate primary-structure deflections. Details of the procedure as well as the computer program RESIST, which is based upon this method, are presented in References 1, 2, and 4.

Natural frequencies obtained with the latest version of the RESIST computer program are presented in Table 3-1. Results are given for a stringer-stiffened panel with no tiles and for panels with tiles of 1.0, 1.6 and 2.3 inch thicknesses. Where possible, solutions are compared with those obtained experimentally (Ref 5) and analytically (Ref 6).

3.3 RESPONSE TO UNIFORMLY CORRELATED RANDOM PRESSURERS

A computer program for the approximate response of shuttle insulation tiles to uniform, spatially-correlated acoustic excitation was developed (Ref 3). This program, titled ARREST, was designed to interface with RESIST. For a dynamics problem, the output of RESIST (which consists of modal frequencies and normalized stresses of stiffened panels with RSI tiles) serves as the input to ARREST. The output of ARREST is approximate in that the analysis is based upon a number of simplifying assumptions. These assumptions are the usual ones* associated with the use of finite element analyses, modal methods, and a smooth broad-band characterization of the acoustic forcing function. Perhaps the most limiting approximation included within ARREST is that the normal pressure field is uniformly correlated over the entire structural panel. This is a conservative assumption that is justifiable for jet noise excitation where the pressure field correlation-length is of the order of the entrance diameter (Ref 10).

If the forcing function is a stationary, random, broad-band acoustic pressure, and the system damping is very small, the mean square response, $(\overline{\delta}_m)^2$, in the m^{th} degree-of-freedon, δ_m, may be approximated as (Ref 10)

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*e.g., linear elastic analysis, modal responses are uncoupled, and each mode responds as if it were a single degree of freedom system excited by "white" noise.

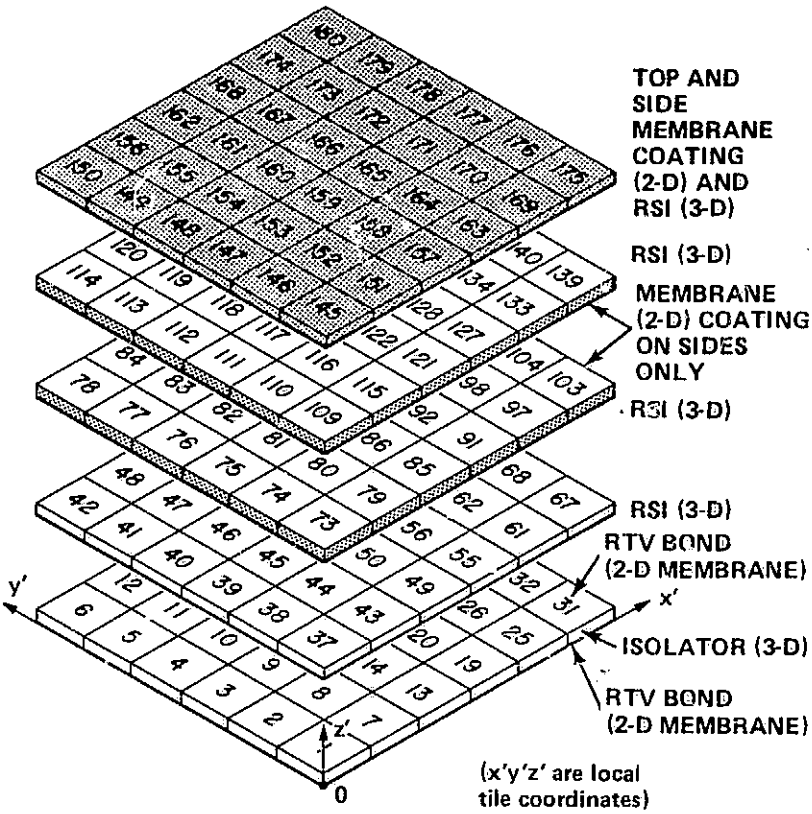

Figure 3-3 Finite Element Idealization of Typical RSI Tile in Local Tile Coordinates

Table 3-1 LRC Panel Frequency Comparisons

Mode Shapes		Frequencies (HZ) Tile Thicknesses, in.								
		0 (No Tiles)			1.0		1.6		2.3	
n*	m**	Tests Ref 5	Analysis of Ref 6	Present Analysis	Analysis of Ref 6	Present Analysis	Analysis of Ref 6	Present Analysis	Analysis of Ref 6	Present Analysis
1	0	97,113	114	107	91	91	80	84	72	77
1	1	130	135	133	109	111	95	100	86	90
1	2	180-184	185	174	150	154	132	132	117	107
1	3	250	246	222	195	204	170	168	150	145
1	4	319	317	313	290	256	245	222	206	183

*n = Number of ½ waves in stringer direction and between supports
**m = Number of ½ waves in cross stringer direction and between supports

$$\bar{\delta}_m^{\,2} \approx \frac{\pi}{4} \sum_i \frac{(\delta_m^{(i)})^2}{M_i^2 \omega_i^3 \zeta_i} S_{ii} \tag{1}$$

S_{ii} is related to the pressure power spectral density, $[S_p(\omega_i)]$ through the relationship

$$S_{ii} = \lfloor A\bar{\phi}_T^{(i)} \rfloor \; [S_p(\omega_i)] \; \{A\bar{\phi}_T^{(i)}\} \tag{2}$$

where $[S_p(\omega_i)]$ (measured in psi^2/radian) may vary spatially over the structure, and and $\{A\,\bar{\phi}_T^{(i)}\}$ are the modal degrees-of-freedom multiplied by suitable terms which account for the local normal surface area over which the pressure excitation acts.

If the pressure distribution is assumed to be "uniformly correlated" (i.e., the time averaged mean square random pressure does not vary spatially over the structure) then $[S_p(\omega_i)]$ is a full matrix with equal elements $S(\omega_i)$ and Eq. (2) simplifies to

$$S_{ii} = S(\omega_i)\left(\sum_j A_{z_j} \bar{\phi}_{T,z_j}^{(i)}\right)^2 \tag{3}$$

where $\bar{\phi}_{T,z_j}^{(i)}$ are the tile degrees-of-freedom, in the i^{th} mode, which are normal to the pressure loading, and A_{z_j} are the corresponding areas over which the pressure loading acts.

A similar approximation for the stress component of a given tile at the j^{th} node, under uniformly correlated random pressure loading, yields

$$\bar{\sigma}_j^{\,2} \approx \frac{\pi}{4} \sum_i \frac{\left(\sigma_j^{(i)}\right)^2}{M_i^2 \omega_i^3 \zeta_i} S(\omega_i) \left(\sum_j A_{z_j} \bar{\phi}_T^{(i)}, z_j\right)^2 \tag{4}$$

for the mean square tile stress. It should be noted that the coefficient for Eqs. (1) and (4) changes from $\pi/4$ to 1/8 if S is given in psi^2/Hz, i.e.,

$$\frac{\pi}{4} S(\omega_i) = \frac{1}{8} S(f_i)$$

where f_i is the i^{th} modal natural frequency in Hz.

3.4 PANEL RESPONSE TO A SHUTTLE LAUNCH ENVIRONMENT

The random sound pressure level curve used to simulate the tiled panel's excitation (Figure 3-4) is thought to be representative of a structural region on the Shuttle orbiter base at liftoff. Detailed results are given for 2.3-inch thick tiles and 2% modal damping. Because of the uncertainty associated with the damping parameter, more conservative results for a 1% critical damping ratio are also presented in Table 3-2.

Normal-to-the-plate RMS acceleration and stress levels for this excitation are presented in Figures 3-5 and 3-6. The associated tile RMS critical stresses, σ_{ZZ}, are plotted in Figures 3-7 through 3-11. Only σ_{ZZ} tile stresses are plotted as the other stress components are generally lower and the RSI material-allowables are several times higher in the x and y directions. Smooth curves are used for the tile RMS stress-plots; however, it should be remembered that the planform idealization for each tile is composed of 6 x 6 x 5 finite element grid. This is somewhat coarse, but adequate, for the present purposes. As shown in Table 3-2, the peak stress levels become critical for a scatter-factor of 3*. This is especially true when the modal damping decreases to 1%.

Comparisons are presented in Table 3-3 and Figure 3-7 with simulation work, based on random processes, performed by Vaicaitis (Ref 7) on the same panel. He considered the random acoustic pressure to be uniform in the cross-stringer direction of the panel but convected as random plane waves in the stringer direction. The model used in his formulation is presented in Reference 6 as well.

Additional tile stresses and panel accelerations for other tile thicknesses, the sound pressure level of Figure 3-4, and 2% of critical modal damping are presented in Table 3-4.

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*A scatter factor of 3, applied to the RMS value, simply means that the probability that a given stress component will be below this value, at any instant, is approximately 99.5%.

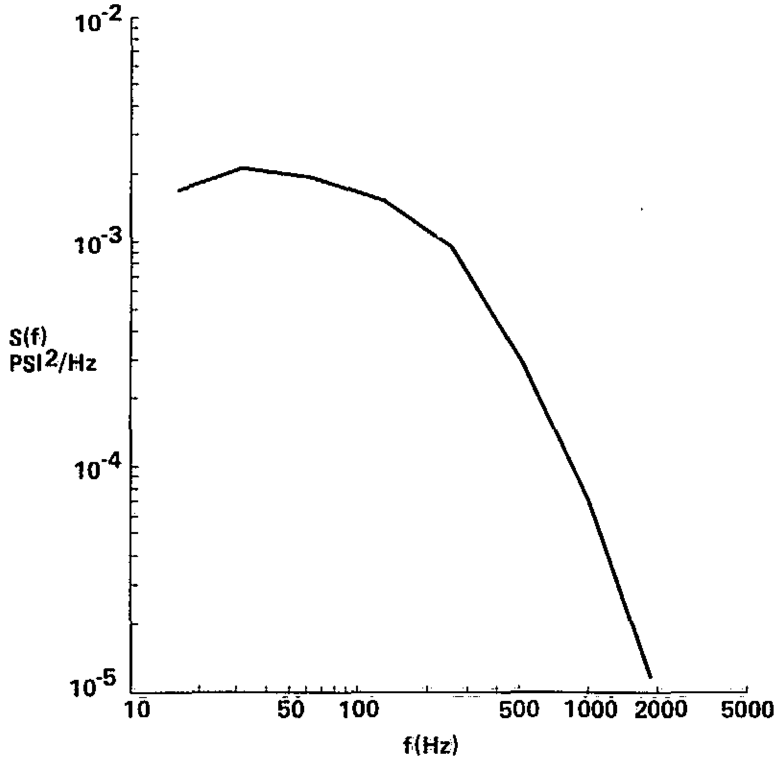

Figure 3-4 Assumed Broad-band Sound Pressure Level Near Base of Orbiter at Shuttle Liftoff

Table 3-2 Critical Tile Stresses for Acoustic Launch Loads

Tile No. (See Figure 2)	Finite Element No. (See Figure 3)	σ_{zz} (psi)*			
		2% Modal Damping		1% Modal Damping	
		RMS	3σ**	RMS	3σ**
1	33	1.501	4.503	2.123	6.368
2	31	1.677	5.031	2.372	7.115
3	34	1.516	4.548	2.144	6.432
7	33	2.174	6.522	3.075	9.224
8	31	2.613	7.839	3.695	11.086
9	34	2.196	6.588	3.106	9.317

*The allowable σ_{zz} for the RSI at room temperature is approximately 8 psi

**The 3σ values correspond to a scatter factor of 3 (i.e., approximately 99.5% probability that the instantaneous stresses will be below this number)

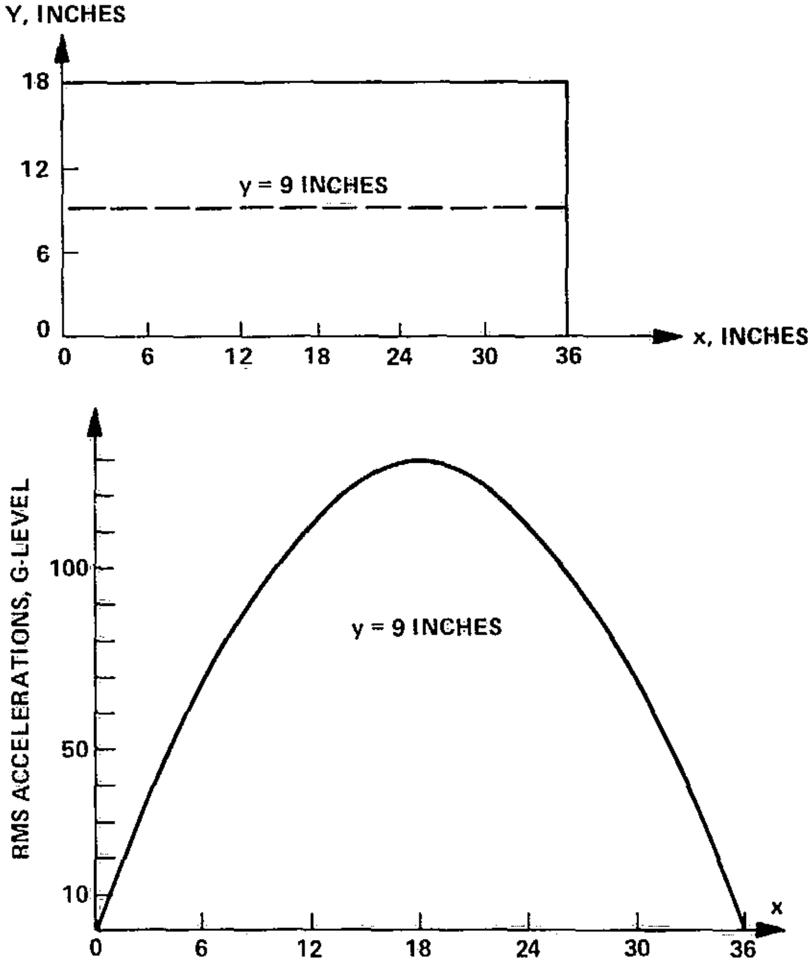

Figure 3-5 Acoustic Response of 2.3-inch RSI Tiled Panel; RMS Accelerations Normal to Plate; 2% Damping.

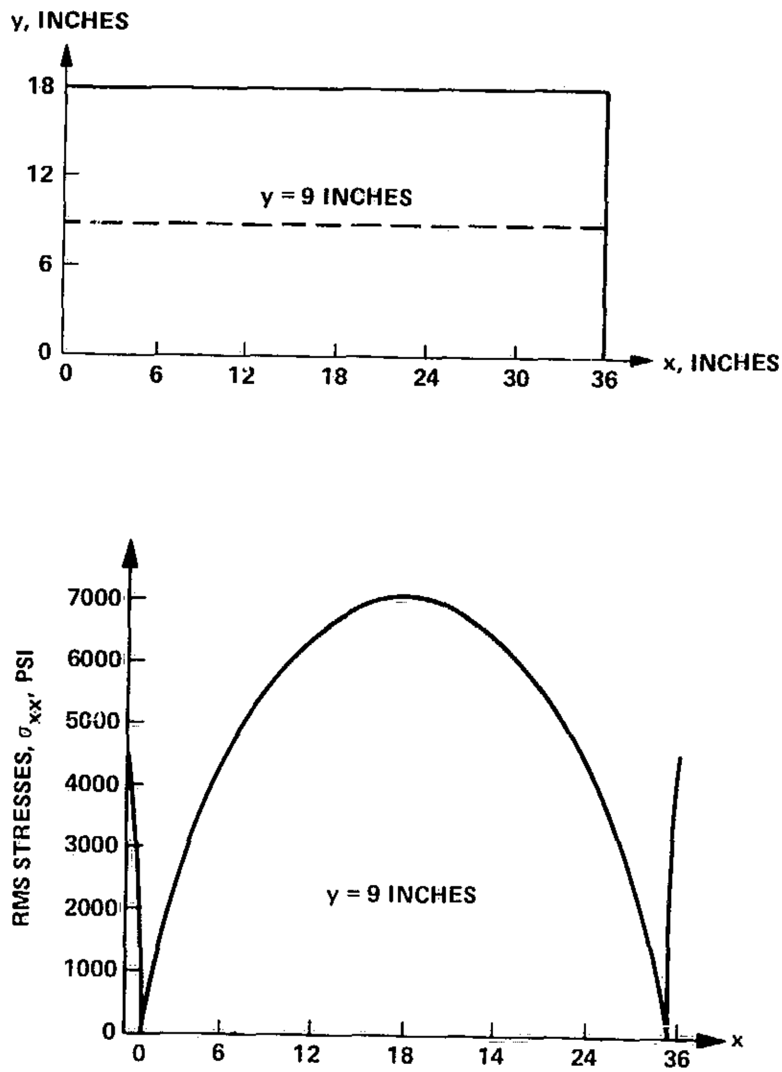

Figure 3-6 Acoustic Plate Stresses at the 2.3-inch Thick Tile Interface

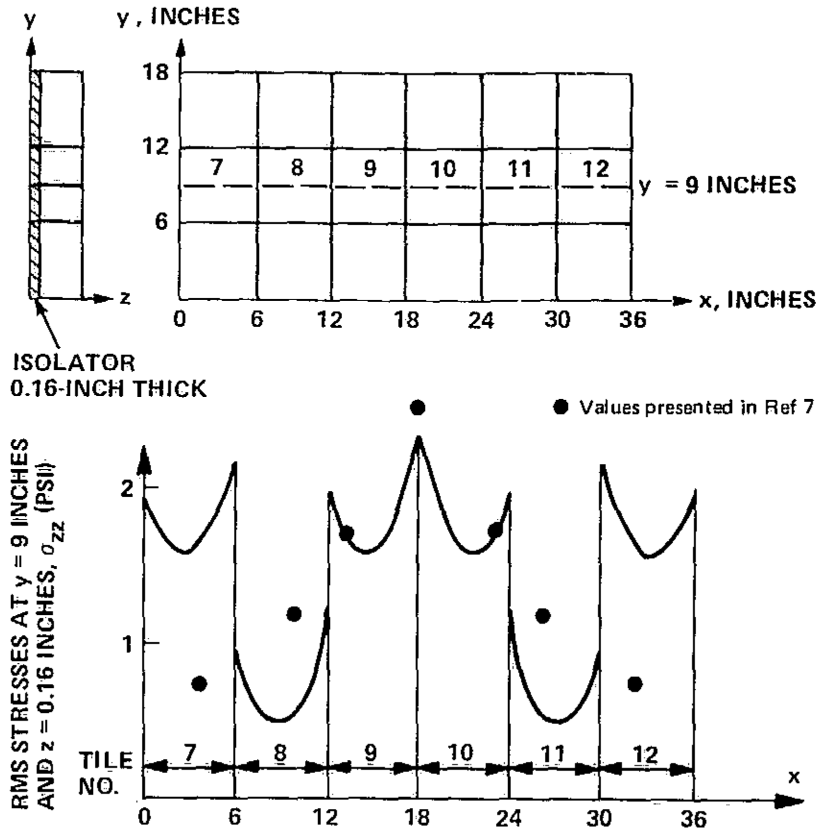

Figure 3-7 Critical Acoustic Stresses Along 2.3-inch Center Tiles (7-12); 2% Modal Damping

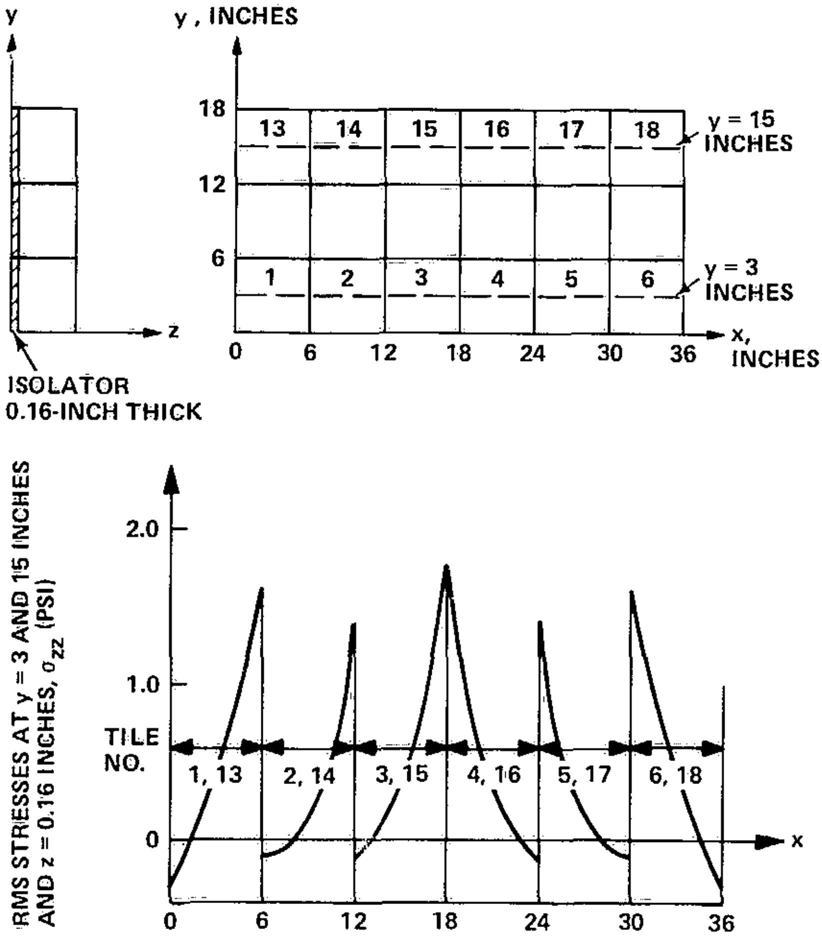

Figure 3-8 Critical Acoustic Stresses Along 2.3-inch Center Tiles; 2% Modal Damping

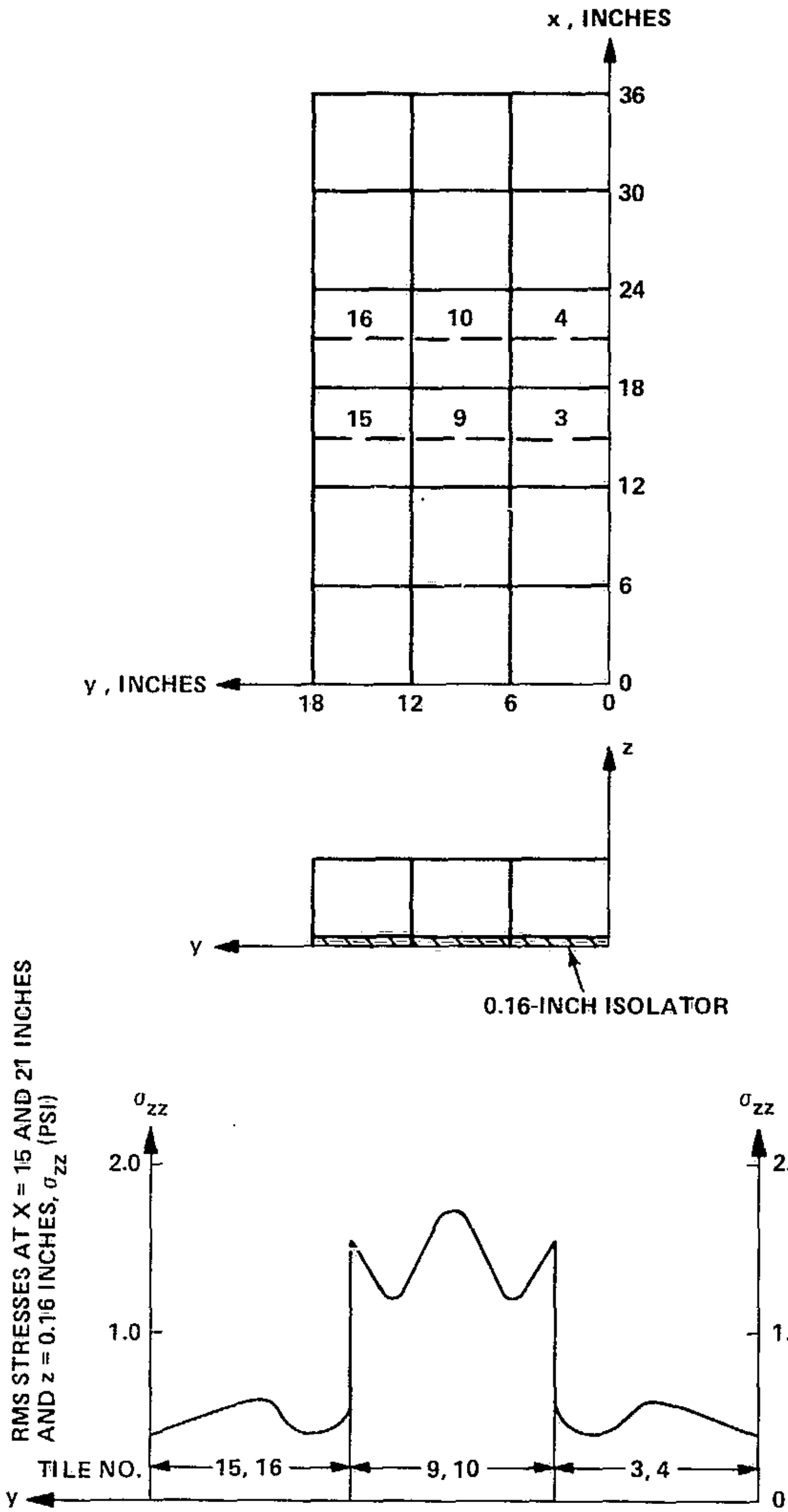

Figure 3-9 Critical Acoustic Stresses Across 2.3-inch Center Tiles; 2% Modal Damping

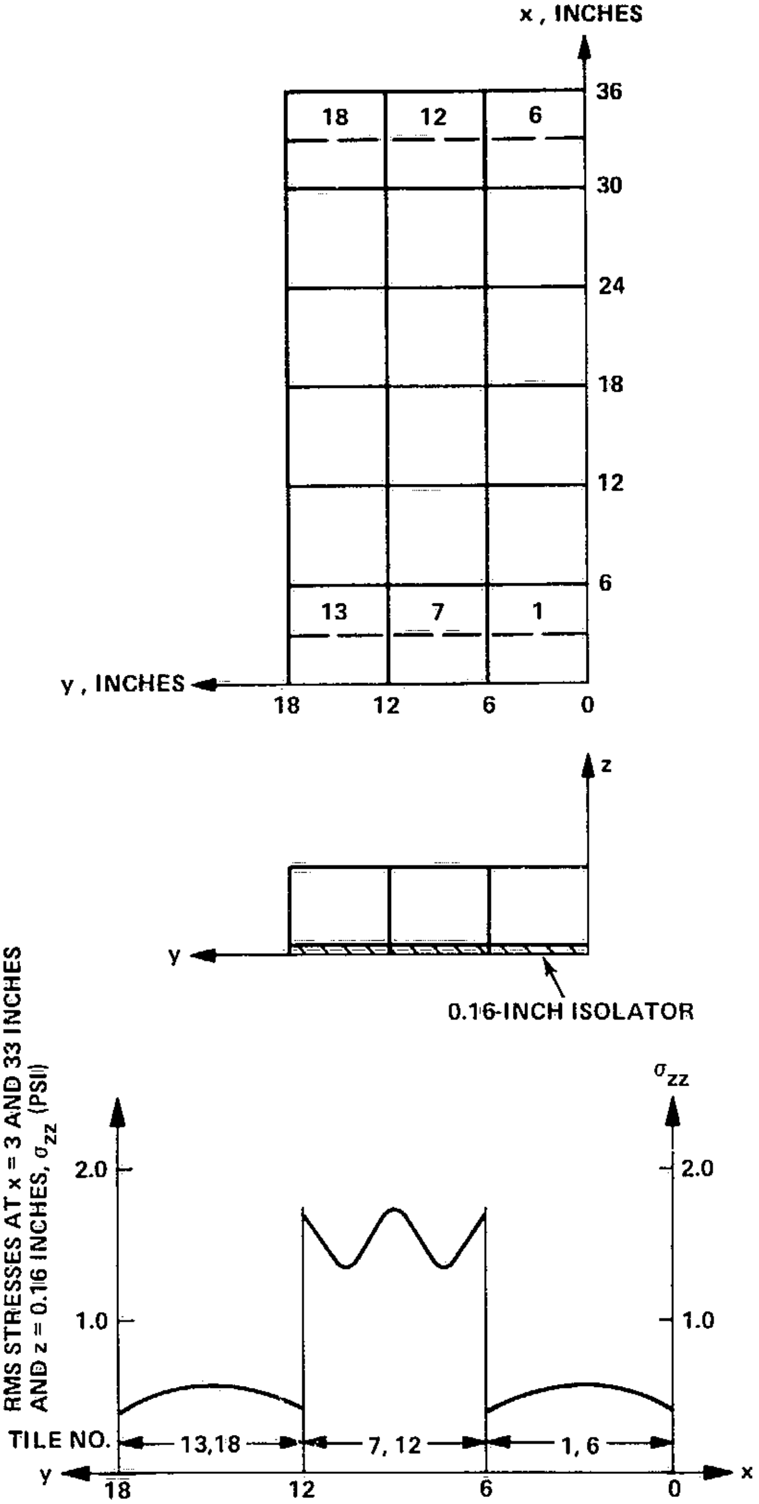

Figure 3-10 Critical Acoustic Stresses across 2.3-inch Tiles Near Supported-Edge of Panel; 2% Critical Damping

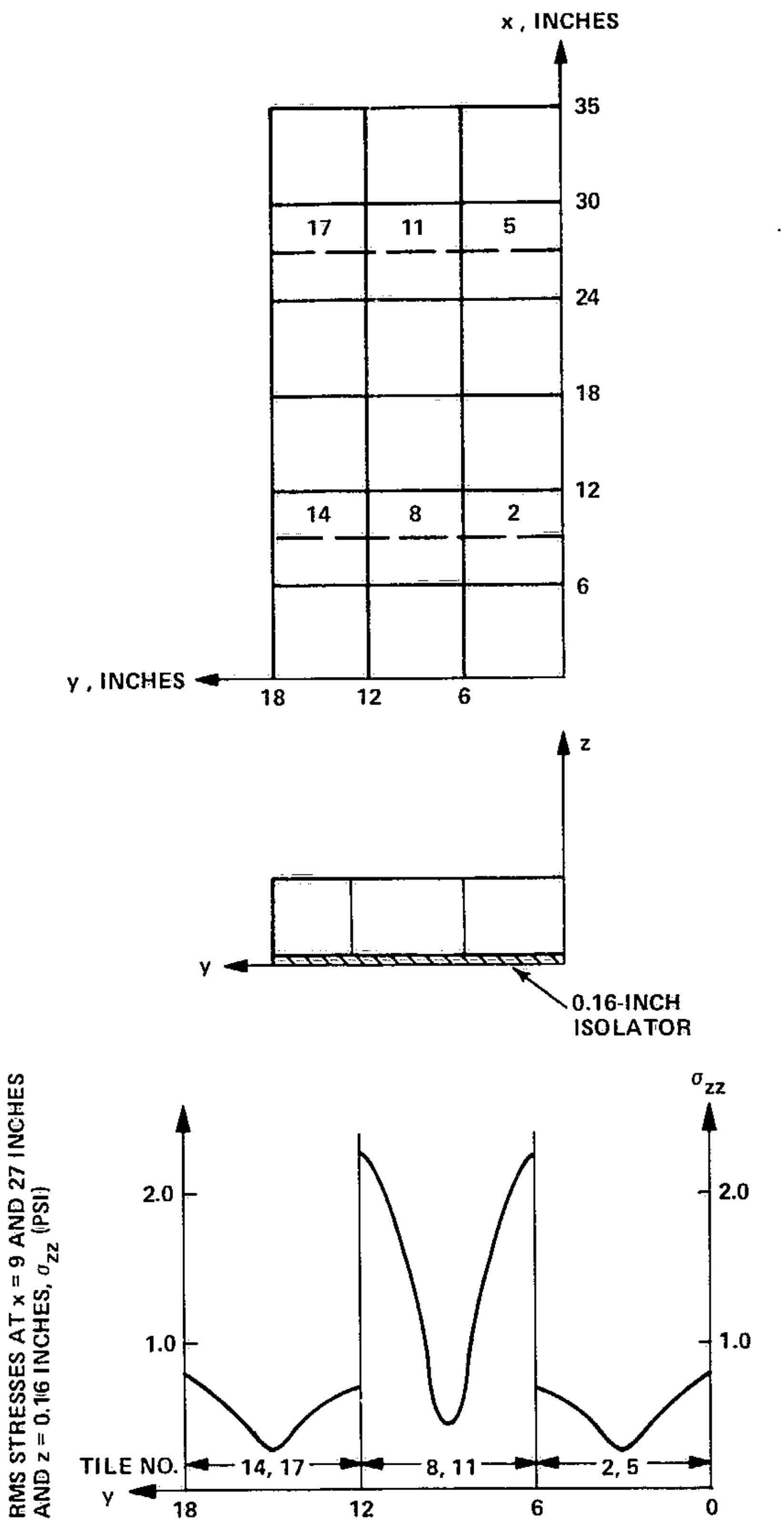

Figure 3-11 Acoustic Stresses across Internal 2.3-inch Tiles; 2% Modal Damping

Table 3-3 Comparison of RMS Panel Response to Acoustic Launch Loads

Tile Thickness (Inches)	Critical Damping Ratio	RMS Deflection (Inches) at Center of Panel		RMS Stringer Stresses (PSI) at Center of Panel	
		Table V of Ref 7	Present Analysis	Table V of Ref 7	Present Analysis
0 (No Tiles)	0.005	0.580	0.618	42,500	44,000
	0.010	0.410	0.437	30,500	31,100
	0.020	0.295	0.309	21,600	22,000
1.0	0.005	0.505	0.444	36,200	32,000
	0.010	0.354	0.314	25,600	22,600
	0.020	0.250	0.222	18,140	16,000
1.6	0.005	0.446	0.442	34,200	32,840
	0.010	0.326	0.312	24,200	23,200
	0.020	0.233	0.221	17,120	16,420
2.3	0.005	0.352	0.436	26,200	33,400
	0.010	0.214	0.308	16,200	23,600
	0.020	0.157	0.218	11,700	16,700
	0.030	0.130	0.178	9,700	13,600

Table 3-4 Peak Tile Stresses and Panel Accelerations vs Tile Thicknesses for SPL $(\omega_1) = 1.8 \times 10^{-3}$ psi^2/HZ and 2% of Critical Damping

Tile Thickness (Inches)	Acceleration at Center of Panel (RMS-G Level)	Maximum RMS Tile Stresses		
		Tile No. (Ref Fig 3-2)	Element No. (Ref Fig 3-3)	σ_{zz} (psi)
1.0	189	1	33	.77
		2	31	.74
		3	34	.77
		7	33	1.39
		8	37	1.67
		9	34	1.40
1.6	162	1	33	1.14
		2	31	1.18
		3	34	1.14
		7	33	1.86
		8	36	2.06
		9	34	1.88
2.3	133	1	33	1.50
		2	31	1.68
		3	34	1.52
		7	33	2.17
		8	31	2.61
		9	34	2.20

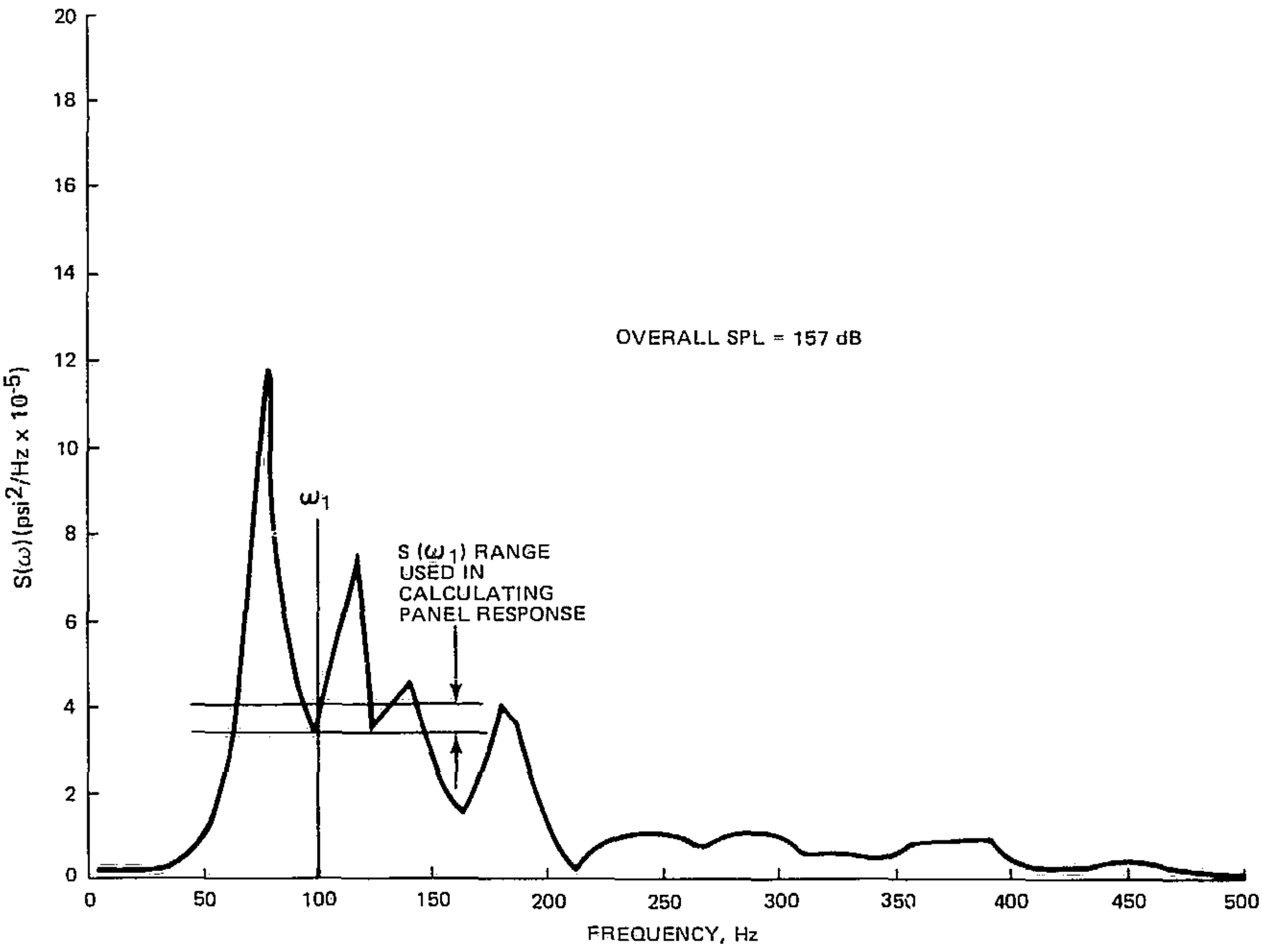

Figure 3-12 Spectrum Sound Pressure Level at Reference Microphone of LRC Test on Untiled panel

3.5 ACOUSTIC RESPONSE COMPARISONS WITH EXPERIMENTS

Acoustic tests, described in Reference 5, have been conducted at Langley upon an untiled panel. Additional unpublished strain data for overall sound pressure levels of 150 dB, 157 dB and 162 dB have also been obtained*. A typical experimental spectrum plot (Figure 3-12) reveals that the excitation level is not smooth but rather peaked near the lower panel frequencies. As such, the assumed conditions upon which the ARREST program is based do not appear to be present in the test facility. Nevertheless, comparisons between measured and predicted strains have been made (see Tables 3-5 and 3-6) to give a general indication of the relevancy of the ARREST program. The locations of the panel strain rosettes and stringer strain gages are indicated in Figures 3-13 and 3-14.

In determining the predicted results, a range of values were obtained. This was due to the uncertain nature of the sound pressure level (see Figure 3-12) and the modal damping at the fundamental panel frequency. The measured modal damping at the fundamental frequency varied between 0.005 and 0.014 (Ref 5). Therefore, by selecting a combination of the lowest measured damping value, together with the highest value of the spectrum sound pressure level at the fundamental frequency, the highest analytical values of Table 3-5 were obtained. Similarly, the lowest analysis values of Table 3-5 were based upon use of the largest measured value of modal damping 0.014 and the lowest sound pressure level at the fundamental panel frequency.

In compiling the measured data* for Table 3-5, it was assumed that the spectrum curves for the 150 and 162 overall dB levels were "similar" in shape, but not magnitude, to the 157 dB level curve. Thus, the 150 dB measured strain results were scaled to 157 dB results by multiplying all the strains by a factor of $\sqrt{10^{.7}}$. Similarly, the 162 dB measured strain results were scaled to 157 dB RMS strains by dividing the 157 dB results by a factor of $\sqrt{10^{.5}}$. Thus, a range is also presented for the measured panel strains. However, the measured stringer strains presented in Table 3-6 are only for the 157 dB overall sound pressure level case. Typical measured strain response spectra are presented in Figures 3-15 and 3-16.

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* Unpublished data received from C. Rucker of the Langley Research Center in September 1976.

Table 3-5 Comparison of Predicted Broad-Band with LRC Measured Narrow-Band Panel Strain Response

Strain Rosette No.	Panel Strain Component Range (Refer to Figure 3-13) (Micro-inches/inch)					
	ϵ_x		ϵ_y		ϵ_{xy}	
	Measured Ref 8	Present Analysis	Measured Ref 8	Present Analysis	Measured Ref 8	Present Analysis
1	55-75	120-232	46-51	20-40	16-19	0
2	54-75	120-232	46-53	20-40	15-16	0
3	58-75	117-226	37-45	19-37	14-18	1-2
5	55-72	119-229	42-45	20-40	16-17	1-2
6	55-72	119-229	45-50	20-40	16-17	1-2
19	44-58	95-183	32-36	15-30	14-15	3-6
20	44-56	95-183	35-38	34-65	15-16	6-11
22	43-57	96-185	36-38	17-32	13-15	3-5
31	33-39	58-113	24-25	9-18	13-14	5-9
32	43-58	60-116	39-43	23-45	15-16	9-18
43	29-33	3-6	18-20	20-38	14	5-10
44	28-32	3-6	19-21	15-29	15-16	16-31
45	28-32	3-6	20-21	26-23	12-14	2-5
46	29-32	3-6	19-21	26-23	11-13	2-5

Table 3-6 Comparison of Predicted Broad-Band with LRC Measured Narrow-Band Panel Strain Response

Strain Gage No.	Stringer Strain ϵ_x (Refer to Figure 3-14) (Micro-inches/inch)	
	Measured Ref 8	Present* Analysis
1	193	326
2	189	318
3	194	312
4	-	320
5	189	313
6	185	318
7	184	327
10	73	326
8	150	255
4	-	320
9	148	255
11	77	326

*Based upon $\zeta_1 = 0.01$ and $S(\omega_1) = 3.5 \times 10^{-5}$ psi^2/Hz.

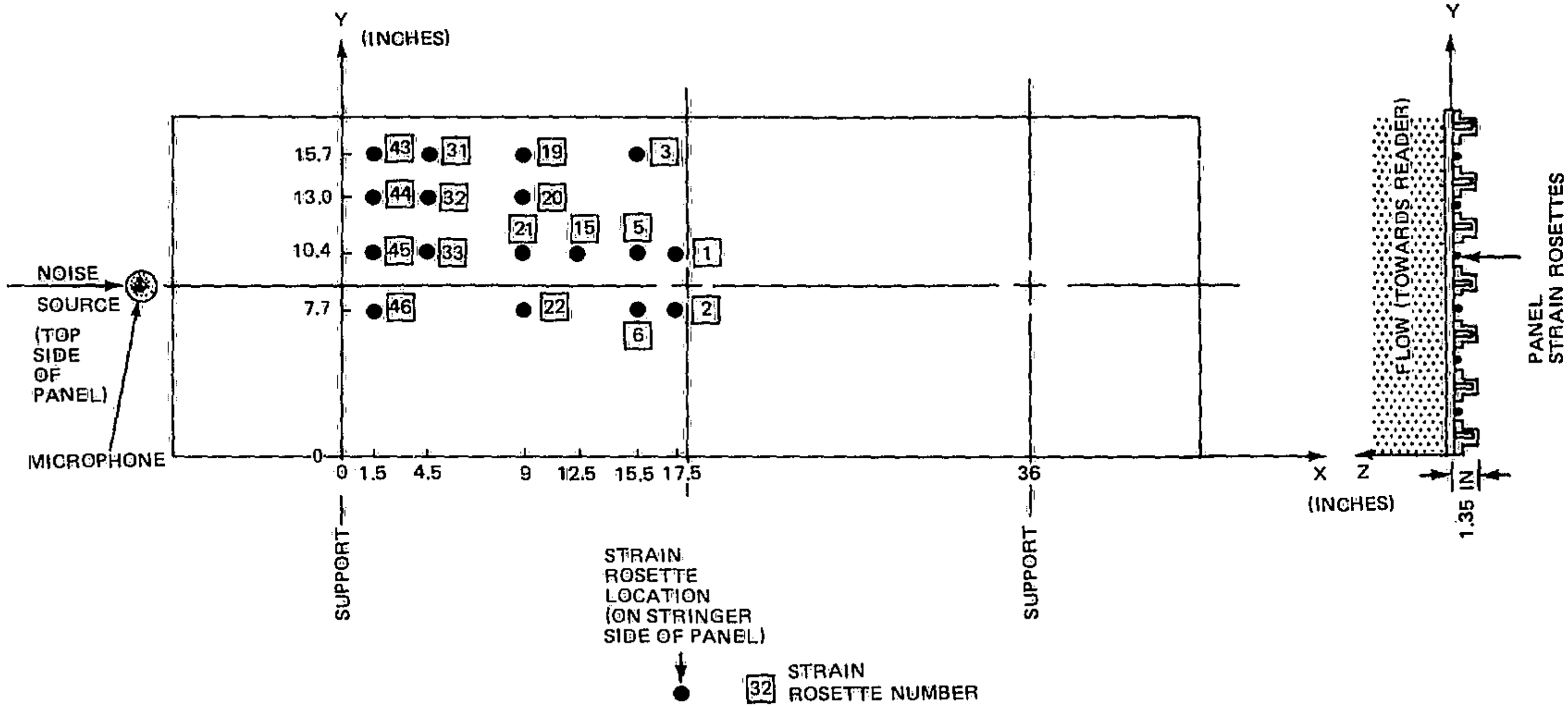

Figure 3-13 Panel Locations for Strain Rosettes on LRC Untiled Shuttle Test Panel

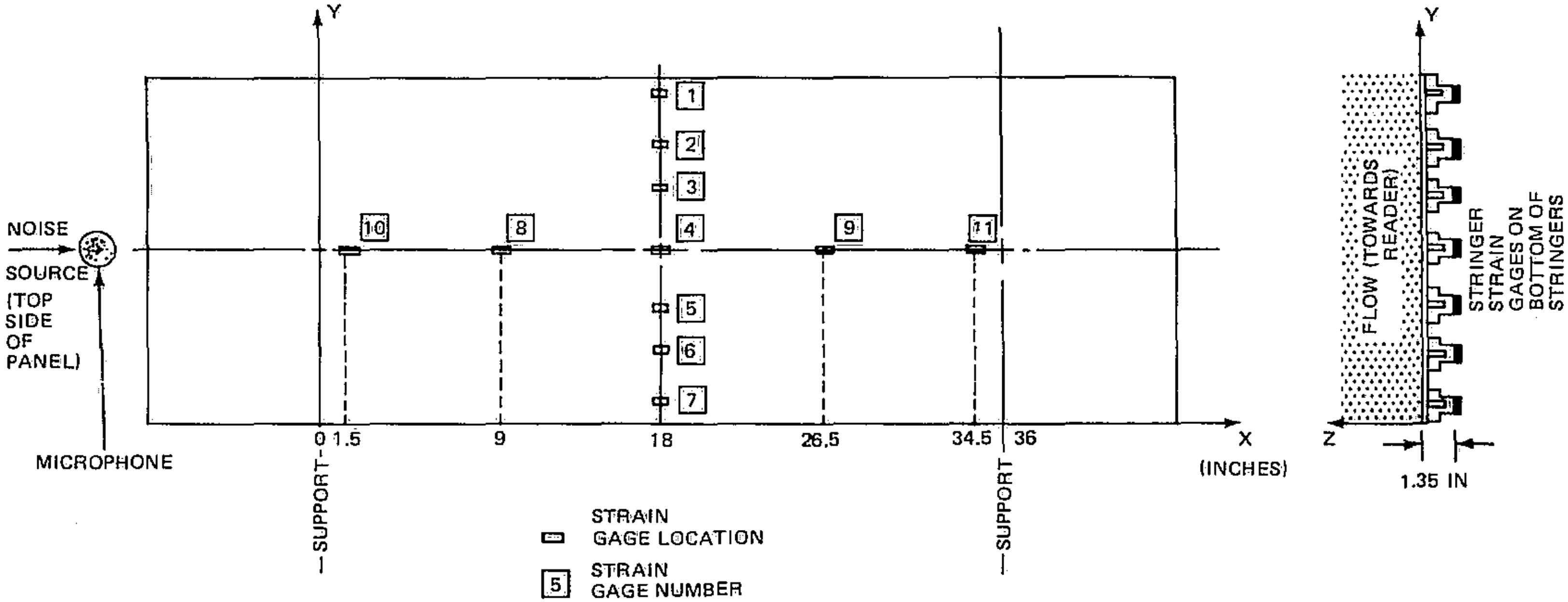

Figure 3-14 Stringer Locations for Strain Gages on LRC Untiled Shuttle Test Panel

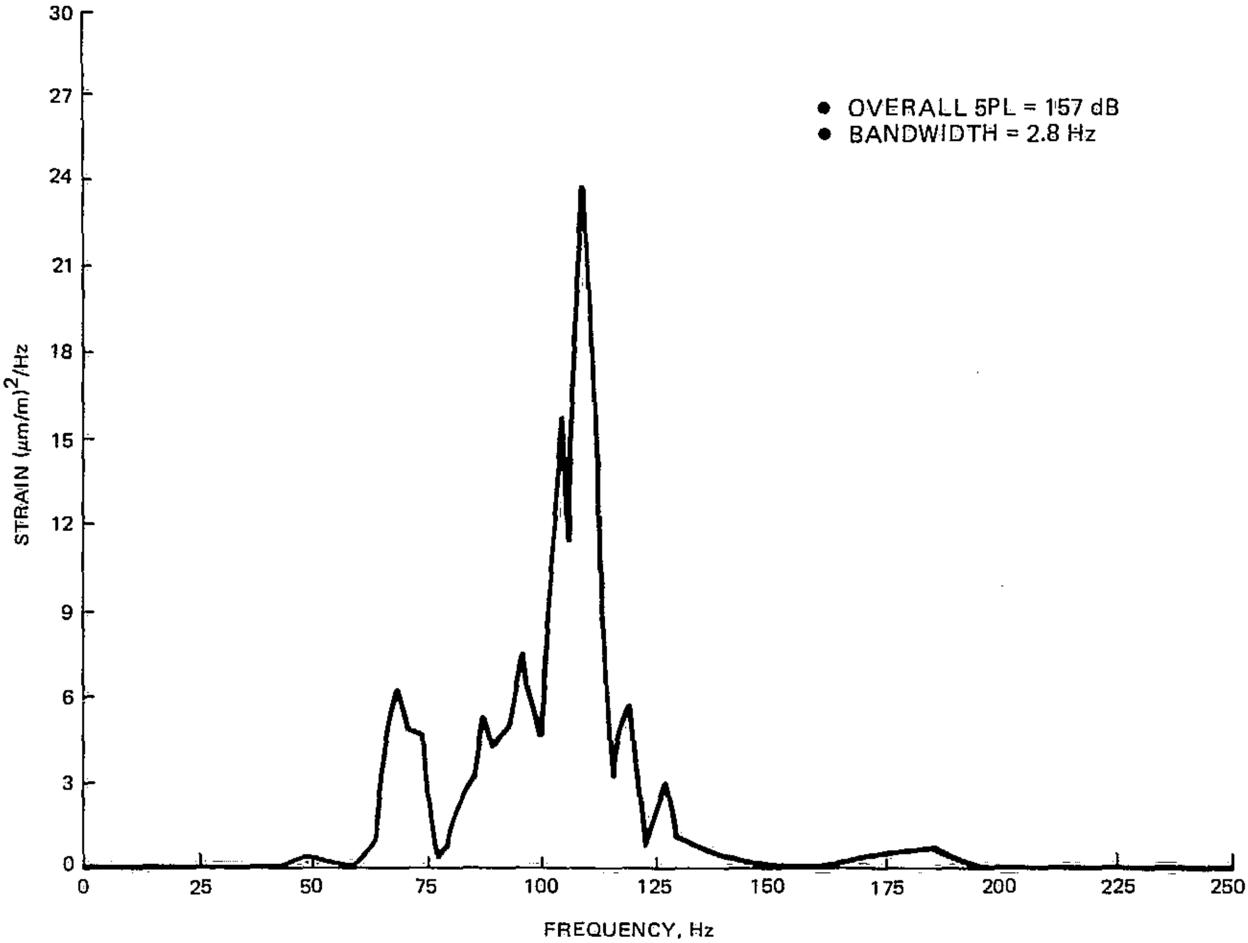

Figure 3-15 Strain Response Spectrum, ϵ_x, for Strain Gage No. 1 (see Fig. 3-13) Mounted on Langley Panel with No Tiles

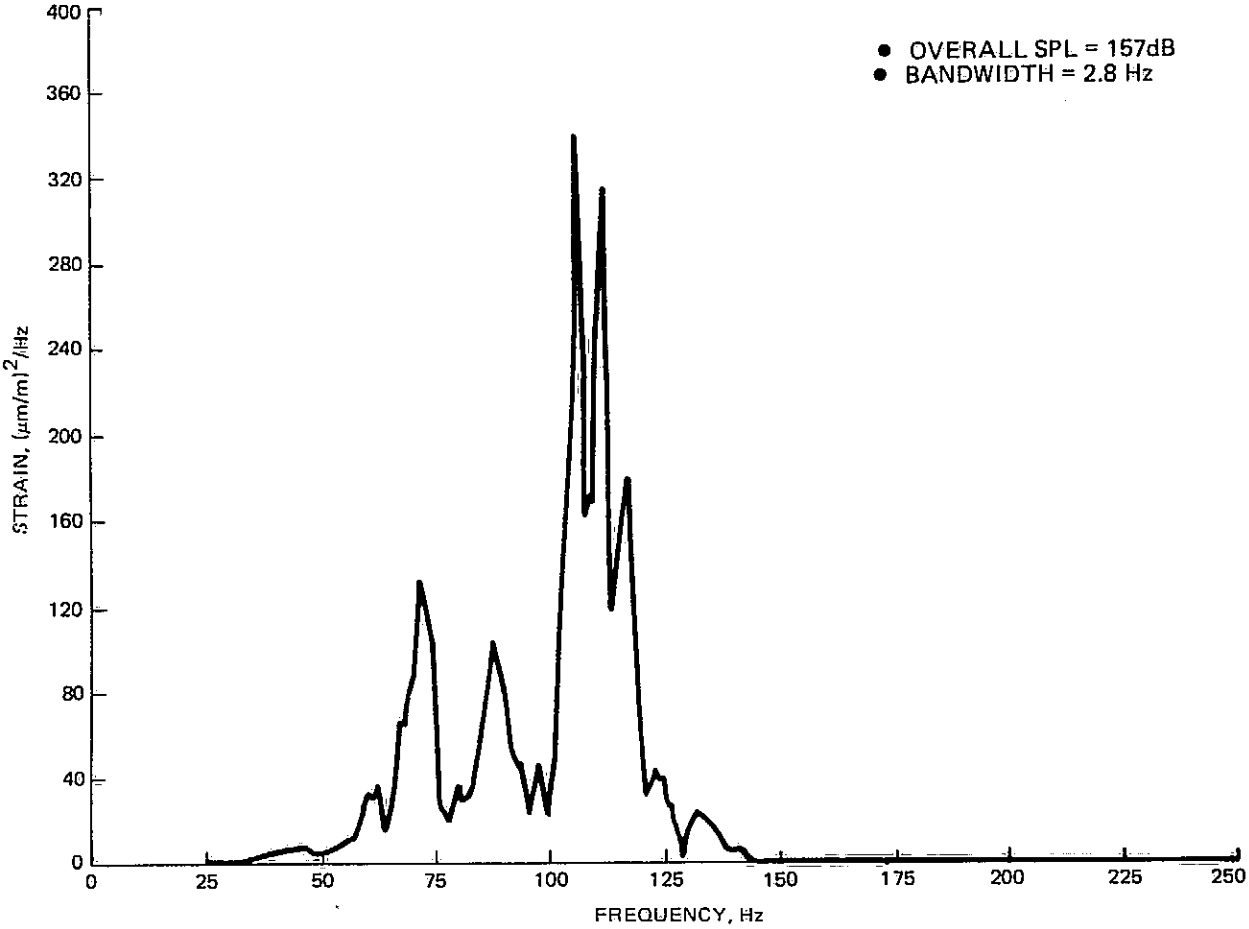

Figure 3-16 Strain Response Spectrum, ϵ_y, for Strain Gage No. 1 (see Fig. 3-13) Mounted on Langley Panel with No Tiles

Section 4

DISCUSSION AND CONCLUSIONS

This report is the third in a series (Ref 2 and 3) which details the development of two user oriented programs for predicting the static, dynamic and thermal stresses in RSI tiles mounted to typical shuttle structure. The objectives of the present phase were to improve the detailed idealization of the RSI tiles and to compare results with experiments and related analyses.

The structural idealization of the tiles has been improved through the inclusion of the effects of a high-temperature coating, part-way down the sides as well as on the top of each tile, and a thin bond layer on either side of the strain isolator plate. This was achieved through the use of additional membrane elements in the finite element modeling of the tiles.

Comparisons of results have also been made with experiments being conducted at NASA/Langley (Ref 5) and related analyses performed at Princeton and Columbia Universities (Ref 6 and 7). However, since these efforts, unlike the programs developed at Grumman Aerospace, were not designed to obtain three-dimensional RSI tile strains,* the only comparisons made with the present approach are based upon panel modes and strain measurements in the sheet and stringers. Therefore, the accuracy of the tile strains computed here can only be inferred from comparisons, which are quite favorable, based upon primary structure responses. It should be noted that the computed results depend heavily upon the accuracy to which the tile material properties are known and the assumption of SIP and RSI material linearity, upon which the program is based.

The present natural vibration results appear to agree well with the experiments and analyses of References 5 and 6, respectively. The main reason for frequency differences are believed to be associated with the fact that the panel tested extends beyond the supports, whereas the panel modeled with the RESIST Program terminates the idealization at the supports. The panel extension was accounted for in the present work in an approximate manner based upon the boundary conditions. Rigid masses were assumed to overhang the supports and to rotate with the stringer slope motions at the supports. Analysis of an actual vehicle panel would have related, if not greater, interaction complexities since the structural panels extend continuously over many bays (e.g. Figure 4-1).

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*An exception to this is found in Reference 6 in which approximate thickness stretching strain in the SIP was obtained.

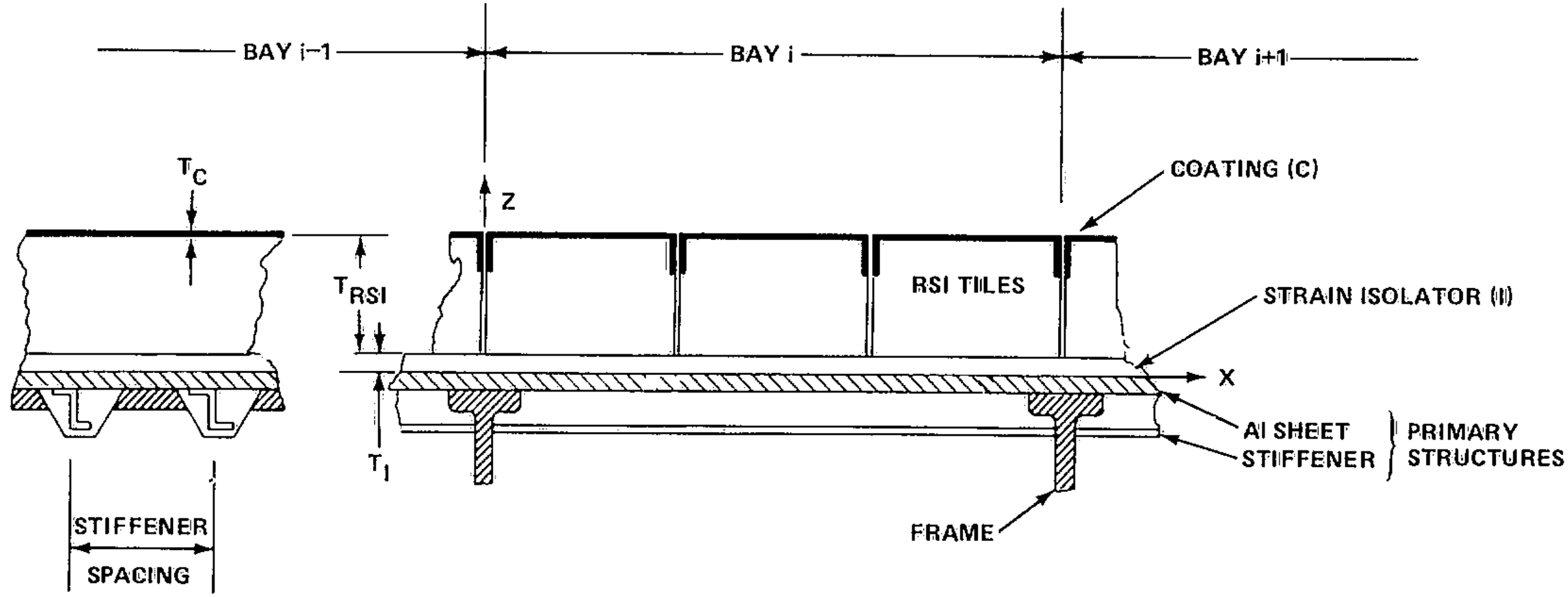

Figure 4-1 Typical Design Configuration for Shuttle Thermal Protection System

Generally speaking, the RMS panel and stringer strains computed here and in Reference 7 are conservatively high as compared to the measured responses. This was anticipated in the present case as the computed values are based upon a theory which is reputed to be conservative (Ref 10). The present theory used simply assumes that the excitation is uniform and spatially correlated, which is unlike the one measured in the experiments. The analysis predicted that the panel response was almost entirely in the first mode, whereas there was evidence of higher modes present in the experiments (see Figures 3-15 and 3-16). Nevertheless, the degree of correlation, the comparisons with Dowell's and Vaicaitis' results (Ref 6 and 7), and the uniqueness of the present program for predicting three-dimensional tile stresses indicates that the RESIST/ARREST combination of programs are highly suitable design analysis tools.

It should be noted that results from the ARREST computer program for a simulated shuttle launch environment indicate potentially critical normal thickness stresses for 1% critical damping, in the thicker RSI tiles. The other RSI stress components, which are not shown, are not critical as they are generally lower and possess strength allowables which are 3 or 4 times higher as well.

Section 5

REFERENCES

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2. Ojalvo, I. U., Austin, F., and Levy, A., "Vibration and Stress Analysis of Soft-Bonded Shuttle Insulation Tiles - Modal Analysis with Compact Widely Spaced Stringers", NASA CR-132553, September 1974.

3. Ojalvo, I. U. and Ogilvie, P. L., "Modal Analysis and Dynamic Stresses for Acoustically Excited Shuttle Insulation Tiles", NASA CR-144958, August 1975, and Proceedings AIAA/ASME/SAE 17th Structures, Structural Dynamics, and Materials Conference, Pa., May 1976 (pp 273-281).

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6. Vaicaitis, R., and Dowell, E.H., "Response of Reusable Surface Insulation Panels to Random Pressure", Proceedings AIAA/ASME/SAE 17th Structure, Structural Dynamics and Material Conference, Pa., May 1976 (pp 257-281).

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8. Newman, M. and Goldberg, M., Private Communication, Polytechnic Institute of New York, 1963.

9. Austin, F. and Ojalvo, I. U., "Convergence of an Iterative Procedure for Large-Scale Static Analysis of Structural Components", AIAA Vol. 14, No. 1, Jan. 1976 (pp 104-106).

10. Dowell, E. H., and Vaicaitis, R., "A Primer for Structural Response to Random Pressure Fluctuations", AMS Report No. 1220, Princeton University, April 1975.

Section 6

NOMENCLATURE

A_{z_j}	Area normal to z direction at j^{th} mode
$\{A\bar{\phi}_T^{(i)}\}$	Product of surface area and i^{th} mode deflection components
f_i	Frequency of i^{th} mode in Hz
f_1	Fundamental frequency
M_i	Modal mass for i^{th} mode
$S(\omega_i)$	Acoustic sound pressure level at i^{th} frequency
S_{ii}	See Eq (3)
$[S_p]$	Pressure power spectral density matrix
x', y', z'	Stringer principal axes
$\delta_m^{(i)}$	Normalized response of the m^{th} degree-of-freedom in the i^{th} mode
$\bar{\delta}_m^2$	Mean square response for the m^{th} degree-of-freedom
ϵ_x, ϵ_y, ϵ_{xy}	Plate membrane strains
ζ_i	Critical damping ratio associated with i^{th} mode
$\bar{\sigma}_j^2$	Mean square response for the j^{th} stress component
$\sigma_j^{(i)}$	Normalized stress response of the i^{th} mode
σ_x, σ_y, σ_{xy}	Plate stress components
σ_{zz}	RSI direct stress component in thickness direction

$\overline{\phi}^{(i)}_{T, z_j}$	Normal (z) deflection of j^{th} tile node associated with i^{th} mode shape
$\{\phi^{(i)}\}$	i^{th} modal vector
ω_i	Natural frequency of i^{th} mode in radians per second

APPENDIX A

USER'S MANUAL FOR

RE*S*I*ST

(STATIC AND DYNAMIC REUSABLE SURFACE INSULATION STRESS PROGRAM)

FEBRUARY 1976 VERSION

A. INTRODUCTION

This Appendix describes the use of a finite element based structural computer program for determining the static response and natural vibrations of TPS protected shuttle panels. The program is titled "RESIST" for static and dynamic REusable Surface Insulation STresses. The logic flow for RESIST is presented in Figure A-1.

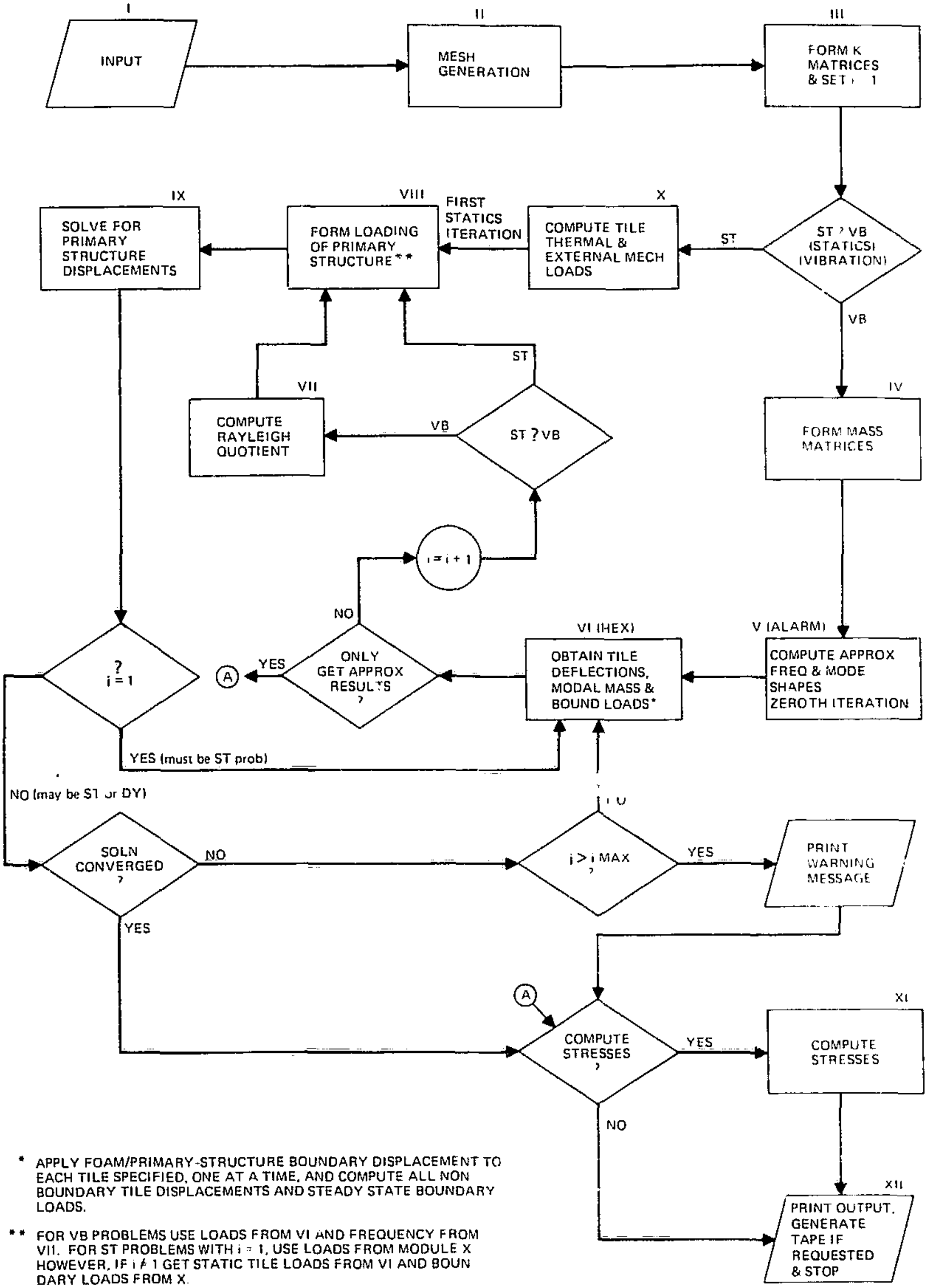
The basis for the method is that the TPS is nonstructural but its stress levels, which are critical, must be computed. Thus, it becomes possible to neglect the stiffness of the TPS initially, but not its mass in the vibration, to determine approximate primary structure deflections.

An iterative procedure is then performed where, for each step, the primary structure deflections are imposed individually upon each tile at the tile/primary-structure interface, and the tile deflections and interface boundary loads are obtained. For the vibration option, the frequency is updated by computing a Rayleigh quotient, using the latest non-rigid tile displacements in addition to the corresponding primary structure displacements. The individual tile boundary loads obtained are then assembled and their reactions are applied to the primary structure. New primary-structure deflections are obtained and compared to the previous set. This process is repeated until convergence is obtained.

B. PROGRAM LIMITATIONS

The usual assumptions for programs based upon the linear elastic finite element method are applicable to RESIST. However, to facilitate the preparation of program input, a number of simplifications regarding the configuration and loadings have been made. Thus, the generation of a voluminous quantity of finite element input data has been greatly reduced by inclusion of a series of data preprocessing subroutines within RESIST. The restrictions upon which these subroutines are based follows:

1. Boundary conditions and edge loadings are assumed uniform along the four rectangular plate edges defined by $x = 0$, L_x and $y = 0$, L_y.
2. The primary structure plate temperature and properties are all uniform.



* APPLY FOAM/PRIMARY-STRUCTURE BOUNDARY DISPLACEMENT TO EACH TILE SPECIFIED, ONE AT A TIME, AND COMPUTE ALL NON BOUNDARY TILE DISPLACEMENTS AND STEADY STATE BOUNDARY LOADS.

** FOR VB PROBLEMS USE LOADS FROM VI AND FREQUENCY FROM VII. FOR ST PROBLEMS WITH i = 1, USE LOADS FROM MODULE X HOWEVER, IF i ≠ 1 GET STATIC TILE LOADS FROM VI AND BOUNDARY LOADS FROM X.

Figure A-1 Flow Chart for RSI Stress Analysis Program "RESIST"

3. The stringers are equally spaced with temperatures and properties which are all uniform.

4. All tiles are geometrically identical as are their temperature distributions and uniform pressure loadings.

5. The boundary conditions must be selected such that the primary structure is statically stable.

The remaining limitations are primarily concerned with the program's capacity and should be adhered to by the user. These limitations are as follows:

6. Maximum number of nodes in a tile = 850.

7. Maximum number of finite elements running in any one direction in a tile = 20.

8. Maximum number of nodes in primary structure = 3000.

9. Maximum number of primary structure nodes along x or y direction = 1,000.

10. Maximum number of degrees of freedom in primary structure = 15,000.

11. Maximum number of natural mode shapes = 50.

12. Maximum number of stringers = 15.

A violation of restrictions 6-12, inclusive, will cause the program to stop and an appropriate warning message to appear.

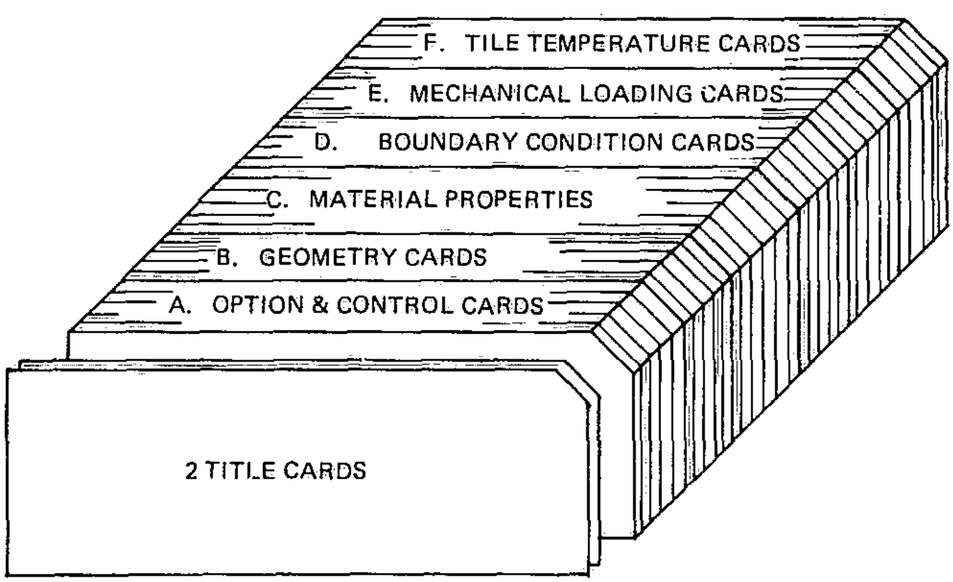
To insure symmetry of solutions for panels which are symmetric with regard to stringer locations about $y = L_y/2$, care should be taken with the input data to see that the plate nodes associated with the stringers are symmetric about $y = L_y/2$.

C. INPUT INSTRUCTIONS

A description of the card input for the IBM 370 and CDC 6600 versions of this program is presented in this section.

In addition to the first two input cards which contain literal data, such as special program title and date, in columns 1 through 80, inclusive; there are six groups of input cards containing the following information:

- Group A - Instructions regarding the type of problem being performed, number of iteratious desired, and type of output information.
- Group B - Details of the geometric configuration and finite element mesh of the primary structure and tiles. (Card B.4 is omitted if there are no tiles)
- Group C - Defines the primary structure and RSI temperature dependent material properties. If there is no TPS, cards C.3 through C.11 are omitted.
- Group D - Specifies the primary structure boundary conditions
- Group E - Describes the mechanical loading upon the primary structure as well as its temperature. These cards are omitted when the vibration option is used
- Group F - Defines the RSI temperature distribution. These cards are omitted if there is no TPS.



A. PROGRAM OPTIONS AND CONTROL — Sheet 1 of 4

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
A.1	1-5	I5	-	-	1 in col. 5 denotes that a statics problem is being treated. Skip cols. 6-25 in such cases
					2 in col. 5 denotes that a natural vibration problem is being treated.
	6-10	I5	N_D	-	Number of desired mode shapes (50 is the maximum permitted).* Omit for statics option.
	16-20	I5	$\bar{s}$	-	Number of reorthogonalizations for eigenvalue algorithm. A min of 2 and a max. of 5 is suggested with 3 as an adequate compromise for most problems. The run should be repeated with greater values for $\bar{s}$ or N_D if the frequency error bound of a desired mode is greater than 1%. Omit for statics option.
	21-25	I5	·	-	Vibration mode number for which modal stresses are desired.** Omit for statics option.
	26-30	I5	i_{max}	-	Maximum number of iterations
	31-40	E10.0	ε	$\{in.^{-1}$ or rad.	Convergence parameter. Maximum primary structure deflection or rotation difference between iterations divided by magnitude of largest element.
	46-50	I5	-	-	0 in col. 50 indicates that primary structure stresses and strains are not required.
					1 in col. 50 indicates that only midplate strains and stresses of primary structure are required.
					2 in col. 50 indicates that only top of plate strains and stresses of primary structure are required.
					3 in col. 50 indicates that only bottom of plate strains and stresses of primary structure are required.
					4 in col. 50 indicates that only mid and top of plate strains and stresses of primary structure are required.
					5 in col. 50 indicates that only mid and bottom of plate strains and stresses of primary structure are required.
					6 in col. 50 indicates that only top and bottom of plate strains and stresses of primary structure are required.
					7 in col. 50 indicates that top, bottom, and mid plate strains and stresses of primary structure are required.
	51-60	E10.0	—	lb-in-sec^2	Overhung rotatory mass inertia associated with each stringer. Used if plate overhange $x = 0$ and $x = L_x$ boundaries.

*If a restart run for a different mode number (i) is contemplated, a tape should be mounted as unit 2 to preserve the mode shapes generated with the present tape.

**If an ARREST run is to be made using information for this mode, provision should be made on control cards to mount tapes as units numbered 1 and 21 for storage and future usage.

A. PROGRAM OPTIONS AND CONTROL - Sheet 2 of 4

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
A.1 (Cont'd.)	61-65	I5	-	-	0 in Col. 65 indicates either no stringers on the plate or that the orthotropic option is being used. 1 in Col. 65 indicates that stringers are attached to plate along only a single rivet or weld line, or have an open cross section. 2 in Col. 65 indicates that stringers have a closed cross section and are attached at double rivet or weld lines.
	66-70	I5	-	-	0 in Col. 70 indicates that orthotropic plate properties are used. 1 in Col. 70 indicates that isotropic plate properties are used.
	71-75	I5	-	-	0 or a 1 in Col. 75 indicates that $K - \omega^2 M$ is decomposed for each primary structure and tile iteration frequency (ω). A 2 in Col. 75 indicates that an iteration procedure which avoids resplitting of $K - \omega^2 M$ is used. This procedure should always be used for statics problems. In addition this approach is generally faster for a vibration problem, but may not always converge.

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
A.2	1-5	I5	-	-	0 in col. 5 indicates that tile stresses are <u>not</u> required. 1 in col. 5 indicates that tile stresses are to be computed after each iteration is performed. 2 in col. 5 indicates that tile stresses are to be computed only after last iteration is performed or only after convergence is obtained.
	6-10	I5	-	-	0 in col. 10 if primary structure stresses and strains were not requested in column 50 of Card A.1. 1 in col. 10 indicates that primary structure stresses and strains are required after each iteration. 2 in col. 10 indicates that primary structure stresses and strains are required only after last iteration or, only after convergence.
	11-15	I5	-	-	0 in col. 15 indicates no tiles on the primary structure. Skip card A.4* 1 in col. 15 indicates that there are tiles on the primary structure.
	16-20	I5	-	-	1 in col. 20 indicates tile node map printout desired. 0 = no node map printout.
	21-25	I5	-	-	1 in col. 25 indicates tile element map printout desired. 0 = no element map printout.
	26-30	I5	-	-	1 in col. 30 indicates tile nodal coordinate, temp. and nodes per element printout. 0 in col. 30 indicates suppression of this printout.
	31-35	I5	-	-	1 in col. 35 indicates printout of element stiffness matrices. 0 = no element stiffness matrices.
	36-40	I5	-	-	1 in col. 40 indicates printout of assembled stiffness matrices and ALARM reorthog. info. 0 in col. 40 indicates suppression of this printout.
	41-45	I5	-	-	1 in col. 45 indicates printout of unit no., file no., and matrix storage info. for program debugging. 0 in col. 45 indicates suppression of this printout.

* If there are no tiles then $\bar{n}_x$ and $\bar{n}_y$, together with n_{B2} and n_{D2}, are still required since they determine the primary structure finite element grid. In analyzing panels without tiles, leave out cards B.4, C.3 through C.10 and all "F" cards.

A. PROGRAM OPTIONS AND CONTROL - Sheet 4 of 4

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
A.3	1-5	I5	IRES	-	1 in Col. 5 if this is a vibration restart run which makes use of primary structure mode shape generated in a previous run.* 0 in Col. 5 if this is not a restart run or if this is a statics problem.
	6-10	I5	-	-	1 in Col. 10 saves a tape which contains a modal solution to be used in ARREST. 0 in Col. 10 does not save such a tape or if this is a statics problem.
	11-20	E10.0	ω	sec^{-1}	Input frequency if IRES = 1 in Col. 5. Leave blank if IRES = 0.
A.4	1-4, 5-8, 9-12, etc.	I4 I4 I4	- - -	- - -	This card is used to indicate which tile stress states are desired. User may specifically request up to 20 tile stress states (see Figure A-3 for tile numbering scheme). A zero in Col. 4 indicates that stress states for all tiles are desired.

*Be sure to indicate, on appropriate job control cards, that this run makes use of an existing tape, mounted as unit 2, which contains the requested mode shape. Provision must also be made on these control cards to have a ring inserted on this tape since it must be written upon in subsequent RESIST calculations.

B. GEOMETRIC CONFIGURATION - Sheet 1 of 2 (See Figure A-2)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
B.1	1-10	E10.0	L_x	in.	Panel dimension
	11-20	E10.0	L_y	in.	Panel dimension
	21-30	E10.0	t_p	in.	Panel thickness
	41-50	E10.0	$\bar{t}$	in.	Stringer effective wall thickness if attached along two plate rivet rows.
	51-60	E10.0	y_2	in.	Distance from y = 0 edge for second attachment row of first stringer.
	61-70	E10.0	Z'	in.	Distance below middle surface of plate at which stringer stress (σ_x) will be computed.

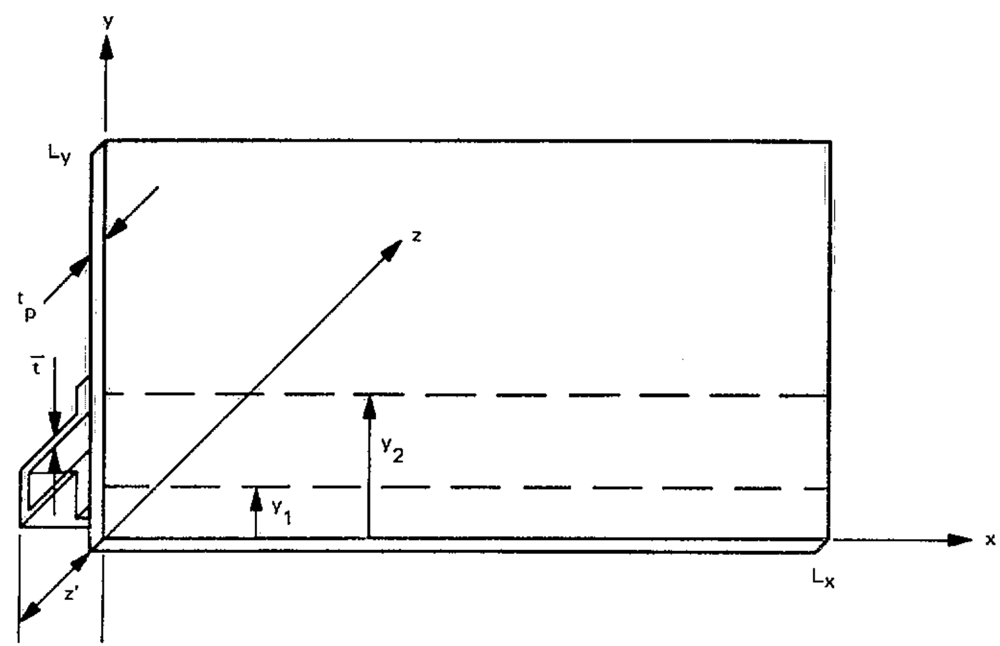


Fig. A-2 Doubly-Connected Stringer Idealization - Global Coordinates

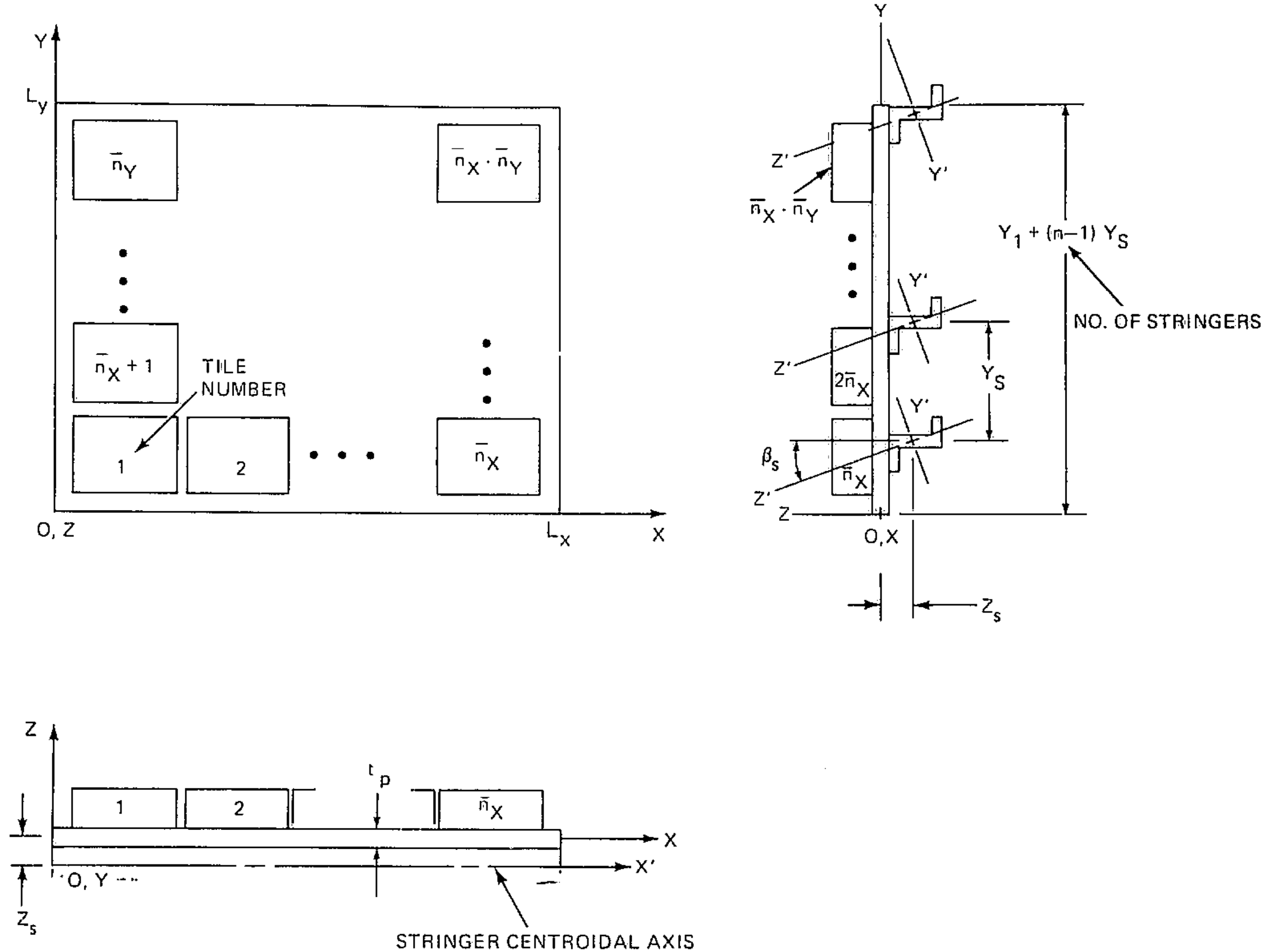


Figure A-3 TPS Configuration on Stiffened Primary Structure - Global Coordinates

B. GEOMETRIC CONFIGURATION - Sheet 2 of 2 (See Figure A-3)

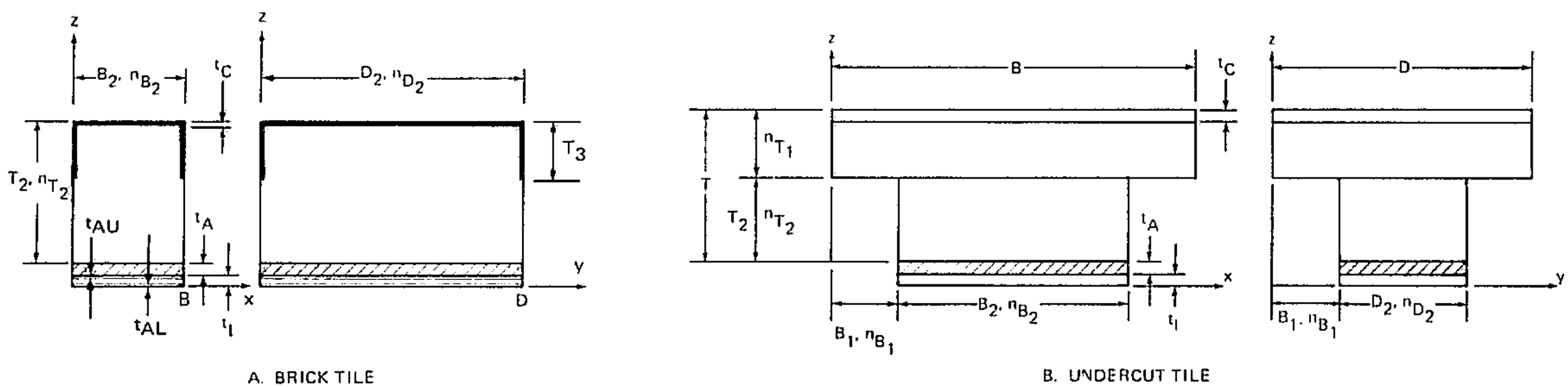
CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
B.2	1-10	8E10.0	Y_1	in.	Position of first stringer attachment row. If there are no stringers, set $Y_1 > L_y$ and skip to the next card.
	11-20	↓	Z_s	in.	Distance of stringer centroid below plate middle surface.
	21-30	↓	Y_s	in.	Discrete stiffener spacing
	31-40	↓	A_s	$in.^2$	Stringer cross sectional area
	41-50	↓	$I_{y'}$	$in.^4$	Stiffener principal mom. of inertia about y' axis
	51-60	↓	$I_{z'}$	$in.^4$	Stiffener principal mom. of inertia about z' axis
	61-70	↓	$J_{x'}$	$in.^4$	Stiffener twisting stiffness geometric parameter
	71-80	↓	β_s	Degrees	Angle between z and z' axis measured positive clockwise along x.
B.3	1-10	I10	$\bar{n}_x$	-	Integer number of tiles between x = 0 and L_x*
	11-20	I10	$\bar{n}_y$	-	Integer number of tiles between y = 0 and L_y*

*If there are no tiles then n_x and n_y, together with n_{B2} and n_{D2}, are still required since they determine the primary structure element grid. In analyzing panels without tiles, leave out cards B.4, C.3 through C.10 and all "F" cards.

B. GEOMETRIC CONFIGURATION – Sheet 2 of 3 (See Figure A-4)

CARD	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
B.4	1-10	6E10.0	T	in.	Undercut RSI tile thickness. Leave blank if tile is brick shaped or if there are no tiles.
	11-20	↓	B_1	in.	Tile undercut dimension. Leave blank if tile is brick shaped.
	21-30	↓	T_2	in.	Tile undercut dimension or, height of brick shaped tile.
	31-40	↓	t_A	in.	Strain arrestor plate (SAP) thickness. May replace with layer of isolator, RSI or bond material if no SAP.
	41-50	↓	t_I	in.	Strain isolator thickness (SIP)
	51-60	↓	t_c	in.	Coating thickness. Leave blank if no tile coating.
B.5	1-10	6E10.0	t_{AL}	in.	Thickness of adhesive which bonds isolator to primary structure (Adhesive Lower)
	11-20	6E10.0	t_{AU}	in.	Thickness of adhesive which bonds RSI tile to isolator. (Adhesive Upper)
	21-30	6E10.0	T_3	in.	Dimension down side of each tile to which coating extends (see Fig. A-4A). Program actually uses integral number of finite element layers (down side of each tile) which is closest to input T_3 value.
B.6	1-5	I5	n_{B_1}	–	Number of elements along B_1. Leave blank if tile is brick shaped or if there are no tiles.

CARD	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
B.6	6-10	I5	n_{B_2}	-	Number of elements along B_2.
	11-15	↓	n_{D_2}	-	Number of elements along D_2.
	16-20	↓	n_{T_1}	-	Number of elements along $T-T_2$. Leave blank if tile is brick shaped.
	21-25	↓	n_{T_2}	-	Number of elements along T_2. Leave blank if no tiles.



NOTE: SUBSCRIPTED SYMBOLS BEGINNING WITH "n" ARE THE NUMBER OF ELEMENTS WHICH SUBDIVIDE THE INDICATED SPAN. THE OTHER SYMBOLS ARE DIMENSIONS.

Figure A-4 RSI Tile Parameters - Local Coordinates

$$
\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} =
\left[\begin{array}{ccc|ccc}
\frac{1}{E_x} & -\frac{\nu_{xy}}{E_y} & -\frac{\nu_{xz}}{E_z} & & & \\
-\frac{\nu_{yx}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{yz}}{E_z} & & \text{NULL} & \\
-\frac{\nu_{zx}}{E_x} & -\frac{\nu_{zy}}{E_y} & \frac{1}{E_z} & & & \\
\hline
 & & & \frac{1}{G_{xy}} & 0 & 0 \\
 & \text{NULL} & & 0 & \frac{1}{G_{yz}} & 0 \\
 & & & 0 & 0 & \frac{1}{G_{zx}}
\end{array}\right]
\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{Bmatrix}
$$

NOTE: This matrix is symmetric; thus, the program insures that

$$\frac{\nu_{xy}}{E_y} = \frac{\nu_{yx}}{E_x}$$

$$\frac{\nu_{xz}}{E_z} = \frac{\nu_{zx}}{E_x}$$

$$\frac{\nu_{zy}}{E_y} = \frac{\nu_{yz}}{E_z}$$

Figure A-5 Orthotropic Stress-Strain Law for 3-Dimensional Elements

C. MATERIAL PROPERTIES - Sheet 1 of 3 (See Figure A-5)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
C.1	1-10	8E10.0	E_p	psi	Isotropic plate modulus of elasticity
	11-20	↓	ν_p	-	Poisson's ratio for plate
	21-30	↓	γ_p	lb/in.^{3}	Weight density for plate
	31-40	↓	α_p	$^oF^{-1}$	Coefficient of thermal expansion for plate
	41-50	↓	A_{11}	psi	Orthotropic plate constants associated with stress-strain law:
	51-60	↓	A_{22}	psi	$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{21} & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$
	61-70	↓	A_{33}	psi	
	71-80	↓	$A_{12}=A_{21}$	psi	
					Comparable symbols used in Reference 5 are: $A_{11} = E'_x$
					$A_{12} = E''$
					$A_{22} = E'_y$
					$A_{33} = G$
C.2	1-10	4E10.0	E_s	psi	Stringer modulus of elasticity (enter zero if no stringers)
	11-20	↓	ν_s	-	Poisson's ratio for stringer
	21-30	↓	γ_s	lb/in.^{3}	Weight density for stringer
	31-40	↓	α_s	$^oF^{-1}$	Coefficient of thermal expansion for stringer

C. MATERIAL PROPERTIES - Sheet 2 of 3 (See Figure A-5)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
C.3	1-10	6E10.0	E_x	psi	Arrestor x direction orthotropic stiffness
	11-20	↓	E_y	psi	Arrestor y direction orthotropic stiffness
	21-30	↓	E_z	psi	Arrestor z direction orthotropic stiffness
	31-40	↓	ν_{xy}	-	See Figure A.5
	41-50	↓	ν_{yz}	-	See Figure A.5
	51-60	↓	ν_{zx}	-	See Figure A.5
C.4	1-10	7E10.0	G_{xy}	psi	See Figure A.5
	11-20	↓	G_{yz}	psi	See Figure A.5
	21-30	↓	G_{zx}	psi	See Figure A.5
	31-40	↓	γ_A	$lb/in.^3$	Weight density for arrestor
	41-50	↓	α_{AX}	$^oF^{-1}$	X coefficient of thermal expansion for arrestor
	51-60	↓	α_{AY}	$^oF^{-1}$	Y coefficient of thermal expansion for arrestor
	61-70	↓	α_{AZ}	$^oF^{-1}$	Z coefficient of thermal expansion for arrestor

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
C.5	1-10	E10.0	E_{Ix}	psi	Isolator x direction orthotropic stiffness
	11-20	E10.0	E_{Iy}	psi	Isolator y direction orthotropic stiffness
	21-30	E10.0	E_{Iz}	psi	Isolator z direction orthotropic stiffness
	31-40	E10.0	ν_{xy}	-	See Figure A.5
	41-50	E10.0	ν_{yz}	-	See Figure A.5
	51-60	E10.0	ν_{zx}	-	See Figure A.5
C.6.1	1-10	E10.0	G_{xy}	psi	See Figure A.5
	11-20	E10.0	G_{yz}	psi	See Figure A.5
	21-30	E10.0	G_{zx}	psi	See Figure A.5
	31-40	E10.0	γ_I	$lb/in.^3$	Weight density for isolator
	41-50	E10.0	α_I	$^oF^{-1}$	Coefficient of thermal expansion for isolator
C.6.2	1-10	E10.0	E_{AL}	psi	Modulus of elasticity of adhesive layer between primary structure and isolator.
	11-20	E10.0	ν_{AL}	-	Poisson's ratio for adhesive layer between primary structure and isolator.

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
C.6.2 (Cont)	21-30	E10.0	α_{AL}	$^{o}F^{-1}$	Coefficient of thermal expansion for bond material between primary structure and isolator.
	31-40	E10.0	E_{AU}	psi	Modulus of elasticity of adhesive layer between RSI or arrestor material and isolator.
	41-50	E10.0	ν_{AU}	-	Poisson's ratio for adhesive layer between RSI or arrestor material and isolator.
	51-60	E10.0	α_{AU}	$^{o}F^{-1}$	Coefficient of thermal expansion for bond material between RSI or arrestor material and isolator.
C.7	1-10	E10.0	γ_R	$lb/in.^3$	Weight density of RSI material
	11-20	E10.0	α_y/α_x	-	RSI coefficient of thermal expansion in y direction ($^{o}F^{-1}$) divided by coefficient of thermal expansion in x direction (α_x).
	21-30	E10.0	α_z/α_x	-	RSI coefficient of thermal expansion ratio in z vs. x direction.

C. TEMPERATURE DEPENDENT MATERIAL PROPERTIES (Sheet 1 of 2)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
C.8.1	1-5	I5	-	-	Number of entry sets in the following table of E_R vs. temperature (°F).
C.9.1	1-10	E10.0	T_1	°F	Temperature (absolute, not relative) corresponding to following value of E_R
	11-20	E10.0	$E_R(T_1)$	psi	Value of E_R (RSI modulus - refer to equations below*) associated with previous temperature.
	31-30	E10.0	T_2	°F	Repeat above set of data as often as necessary, 4 sets to a card.
	etc.	etc.	etc.	etc.	Program uses closest 3 data pts. for 2nd order Langrangian interpolation of properties if element temperature is within data specified temperature range and at least 3 data-points are input. Program uses closest data-point properties for element temperature outside range. Uniform property value is used for any given property if only one value of that property is specified. Thus, program requires a minimum of 1 or 3 value(s) per property for proper execution.

*For RSI (refer to Figure B-4)

$$E_x = E_y = E_R \qquad \nu_{xy} = \nu_{yx} = \nu_R \qquad G_{xy} = G_{yx} = \frac{E_R}{2(1 + \nu_R)} \qquad \nu_{xz} = \nu_{yz} = \nu'_R$$

$$E_z = E'_R \qquad \nu_{zx} = \nu_{zy} = \frac{E_R}{E'_{R_R}} \nu'_R \qquad G_{yz} = G_{zy} = G_{xz} = G_{zx} = G'_R$$

C. TEMPERATURE DEPENDENT MATERIAL PROPERTIES - Sheet 2 of 2

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
C.8.2 & C.9.2	-	E10.0	E'_R	psi	Repeat above two card sets for E'_R*
C.8.3 & C.9.3 through C.8.6 & C.9.6	-	E10.0	-	-	Repeat above card sets for remaining RSI properties in following order: G'_R, ν_R, ν'_R, and α_x where α_x = RSI coefficient of thermal expansion in x direction.
C.10.1 & C.11.1 through C.10.3 & C.11.3	-	E10.0	-	-	Repeat above card sets for coating properties in following order: Leave this card blank if there is no coating. E_c, ν_c, α_c

D. BOUNDARY CONDITIONS — Sheet 1 of 4 (See Figure A-6)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
D.1, D.2, D.3, D.4	1	A1	-	-	A denotes the x=0 edge of the plate (CARD D.1) B denotes the $x=L_x$ edge of the plate (CARD D.2) C denotes the y=0 edge of the plate (CARD D.3) D denotes the $y=L_y$ edge of the plate (CARD D.4)
These are four similar boundary condition cards	2	A1	-	-	0 indicates that the plate edge is free to deflect and rotate out of the z=0 plane (FREE) 1 indicates that the plate edge is not free to deflect or rotate out of the z=0 plane (CLAMPED) 2 indicates that the plate edge is not free to deflect but is free to rotate out of the z=0 plane (PINNED) 3 indicates that the plate edge is flexibly held with regard to out of plane motion
	3-11	E9.0	K_{ww}	$lb/in.^2$	Out-of-plane force per unit edge-length caused by out-of-plane unit deflection
	12-20	↓	$K_{w\theta}$ or $K_{\theta w}$	lb/in.	Out-of-plane force per unit edge-length caused by out-of plane unit rotation or Out-of-plane moment per unit edge-length caused by out-of-plane unit deflection
	21-29	↓	$K_{\theta\theta}$	lb	Out-of-plane moment per unit edge-length caused by out-of plane unit rotation

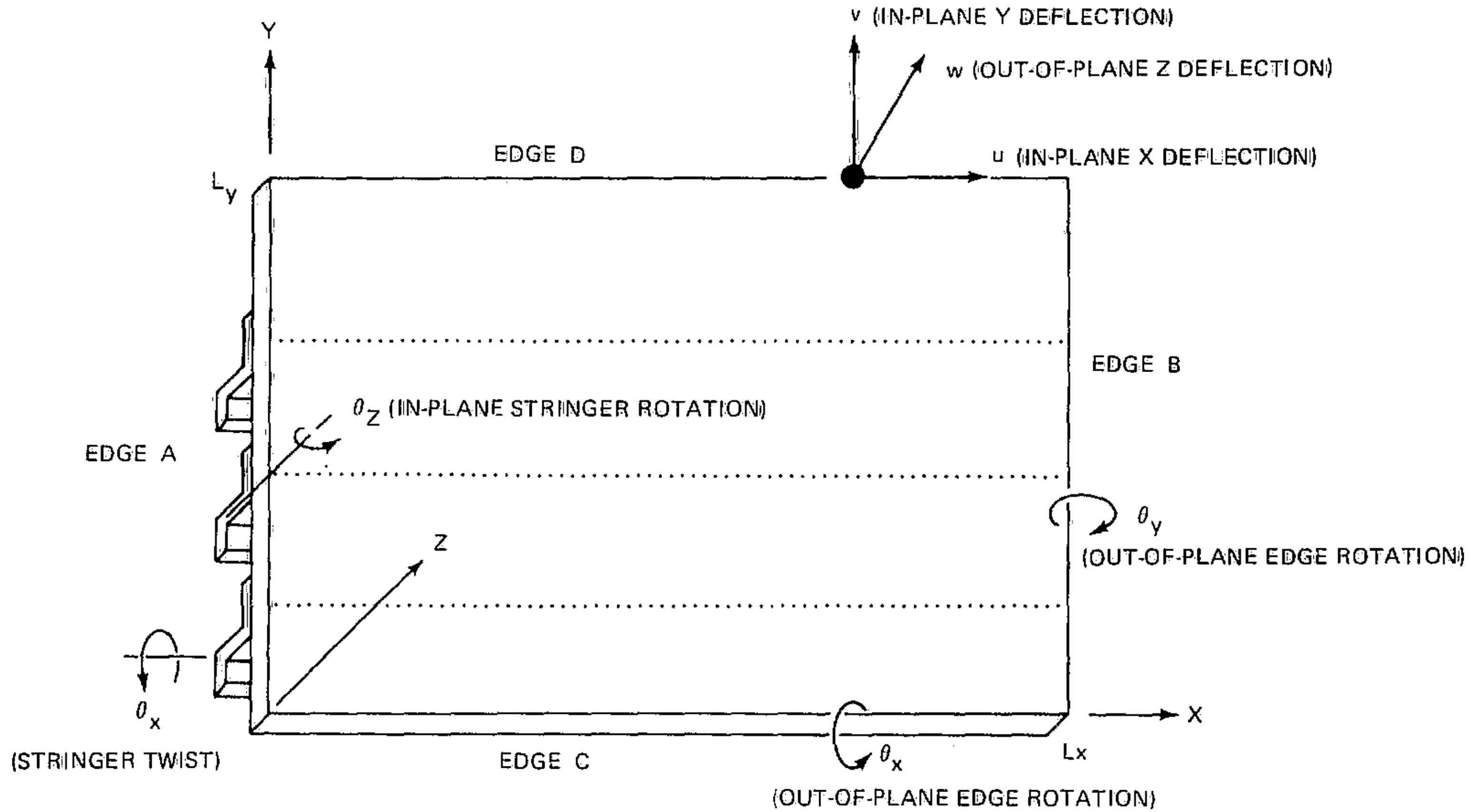


Figure A-6 Primary Structure Boundary Condition Notation - Global Coordinates

D. BOUNDARY CONDITIONS — Sheet 2 of 4 (See Figure A-6)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
D.1–D-4, (continued)	31	A1	-	-	0 denotes edge is not held from in-plane deflections 1 denotes edge is held from in-plane deflections 2 denotes edge is not held for y deflection, but is held for x deflection (PARTIALLY HELD) 4 denotes edge is not held for x deflection, but is held for y deflection (PARTIALLY HELD) 3 denotes edge is flexibly held for in-plane deflections NOTE: For non-vibratory heated or cooled primary structure problems, refer to special instructions on bottom of page A-23/24.
	32-40	E9.0	K_{uu}	$lb/in.^2$	In-plane x force per unit length on an edge caused by in-plane x direction unit deflection
	41-49	↓	K_{uv} or K_{vu}	$lb/in.^2$	In-plane x force per unit length on an edge caused by in-plane y direction unit deflection or In-plane y force per unit length on an edge caused by in-plane x direction unit deflection
	50-58	↓	K_{vv}	$lb/in.^2$	In-plane y force per unit length on an edge caused by in-plane y direction unit deflection

D. BOUNDARY CONDITIONS — Sheet 3 of 4 (See Figure A-6)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
Add'l info. for cards D1 and D2 only.	60	A1		-	0 denotes stringer edge not held for in-plane rotation (θ_z) 1 denotes stringer edge held for in-plane rotation ($\theta_z = 0$) 3 denotes stringer edge flexibly held for in-plane rotation Note θ_z is not a primary structure degree of freedom unless a stringer element is also present at a particular plate node
	61-69	E9.0	$K_{s\theta_z}$	in.-lb	In-plane stringer edge moment produced by unit rotation θ_z
	71	A1	-	-	0 denotes stringer edge free to twist (θ_x) 1 denotes stringer edge not free to twist ($\theta_x = 0$) 3 denotes stringer edge flexibly held against twist
	72-80	E9.0	$K_{s\theta_x}$	in.-lb	Twist moment on end of stringer for a unit twist-rotation

Special Instructions for running a thermal stress problem, when the primary structure is at a uniform temperature other than the reference temperature, are required to permit free in-plane thermal straining; e.g.:

1. Permit the x=0 boundary to move freely or be elastically held in-plane
2. Permit the $x=L_x$ boundary to move freely in the y direction but not the x direction if free, or be elastically held if also elastically held along x=0.
3. Permit the y=0 boundary to move freely or be elastically held in-plane.
4. Permit the $y=L_y$ boundary to move freely in the x direction but not the y direction if free, or be elastically held if also elastically held along y=0.

D. BOUNDARY CONDITIONS - Sheet 4 of 4 (See Figure A-6)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
D.5*	1	A1	-	-	A denotes boundary condition for closed section stringer on $x = 0$ edge.
	5	I4	-	-	0 in Col. 5 indicates that the closed section stringer is not held against stretching at the $x = 0$ edge 1 in Col. 5 indicates it is held in stretching.
	10	I5	-	-	0 in Col. 10 indicates that the closed-section stringer is not held against twisting at the $x = 0$ edge. 1 in Col. 10 indicates it is held against twisting.
	15	I5	-	-	0 in Col. 15 indicates that the closed-section stringer is not held against out-of-plane bending at the $x = 0$ edge. 1 in Col. 15 indicates it is held against out-of-phase bending.
	26	A1	-	-	B denotes boundary condition for closed-section stringer on $x = L_x$ edge
	30	I4	-	-	Same as for Col. 5 on $x = L_x$ edge
	35	I5	-	-	Same as for Col. 10 on $x = L_x$ edge
	40	I5	-	-	Same as for Col. 15 on $x = L_x$ edge

*This card is required only if the stringer sections are closed and are attached at multiple plate rivet lines.

E. PRIMARY STRUCTURE LOADING (See Figure A-7)

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
E.1	1-10	8E10.0	N_x	lb/in.	Uniform, direct cover-plate running load in x direction on x = 0 edge (see Figure 7)
	11-20	↓	N_y	lb/in.	Uniform, direct cover-plate running load in y direction on y = 0 edge (see Figure 7)
	21-30	↓	N_{xy}	lb/in.	Uniform, shearing cover-plate running load on x = 0 edge (see Figure 7)
	31-40	↓	N_{yx}	lb/in.	Uniform, shearing cover-plate running load on y = 0 edge (see Figure 7)
	41-50	↓	P_z	psi	Uniform external normal pressure acting upon tiles
	51-60	↓	T	lb	Tension force acting upon centroid of each stiffener at x = 0
	61-70	↓	M	in.-lb	Out-of-plane bending moment acting upon each stiffener
	71-80	↓	V	lb	Shear load acting upon each stiffener
					Note, boundary conditions for B and D edges should be selected carefully to produce desired effect, e.g. to produce a uniform primary structure tension in the x direction, $\sigma_x = \bar{\sigma}$ and $\sigma_y = 0$: set $N_x = t_p \bar{\sigma}$, $T = A_s \bar{\sigma}$, and P_z, M and V all equal to zero; then hold plate edge B from in plane x, but not y, motion and also hold the stringers at edge B; next, make edges C and D free for x motion, and only hold one of these edges against y motion.
E.2	1-10	E10.0	ΔT_p	F^o	Temperature difference of plate from T_{Ref}.
	11-20	E10.0	ΔT_s	F^o	Temperature difference of stringers from T_{Ref}.

Note: Leave out cards E.1 and E.2 if vibration option is used

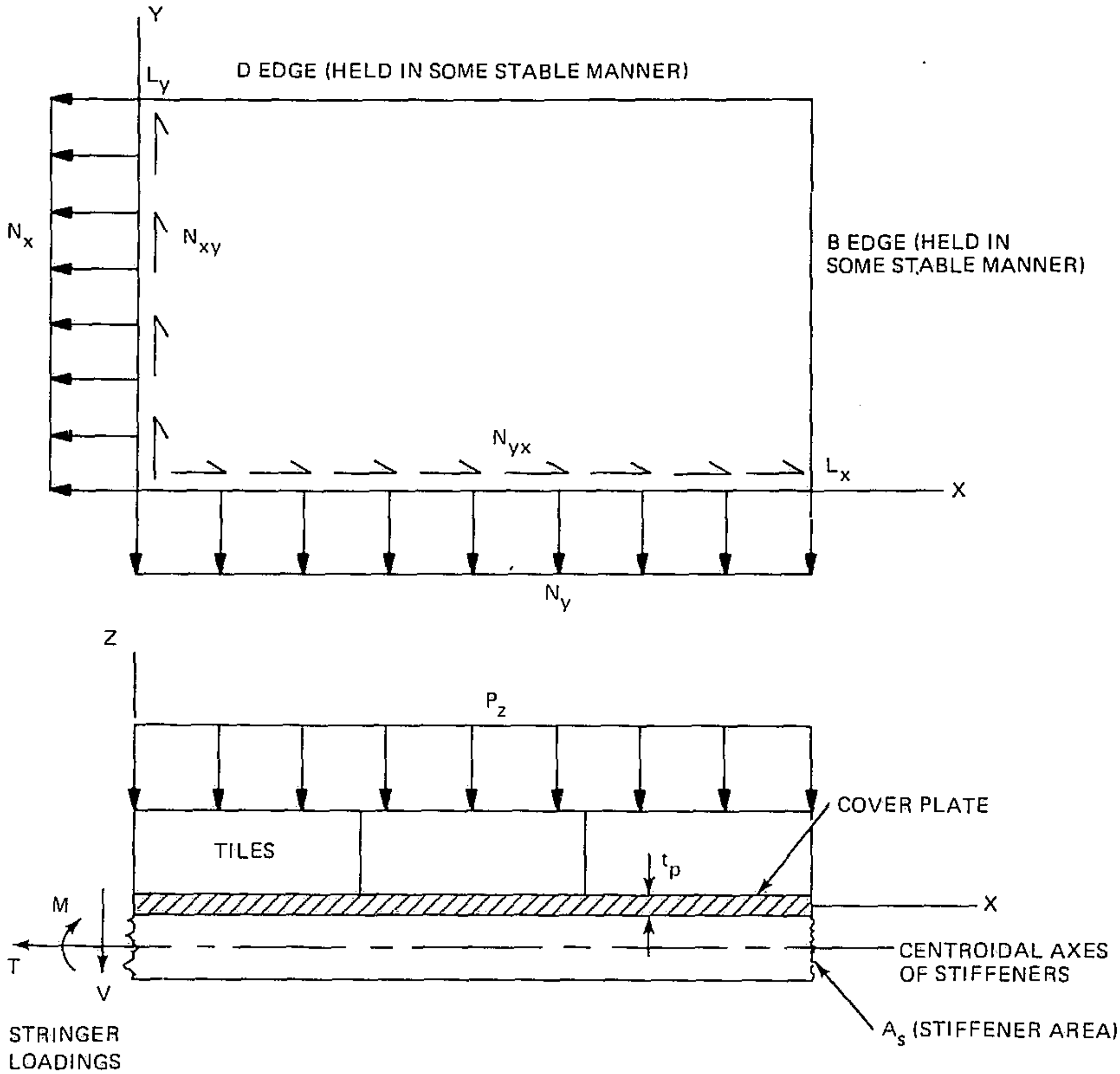


Figure A-7 Possible Static Mechanical Loadings Upon Panel - Global Coordinates

F. TILE TEMPERATURE DISTRIBUTIONS – Sheet 1 of 2

Each tile is assumed to have the same temperature distribution. There are 3 temperature distribution options, each of which is considered separately below. Tile temperature differences, rather than absolute tile temperatures, are required for each of these options (since thermal strains depend upon temperature differences). However, since temperature-dependent material property data are presented in terms of absolute temperature scales, a reference temperature (which is also input) is added to the differences to obtain absolute temperatures for internally computing material properties. Omit all F cards if there are no tiles.

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
F.1	5	I1	-	-	0 in col.5 of this card indicates no thermal static loading effects will be considered. But material properties used in forming the TPS stiffness properties will be based upon the specified temperature distribution. 1 in col. 5 indicates that thermal static loading will be considered in the analysis. In such cases, refer to bottom of following page for special instructions regarding boundary condition cards (D.1 through D.4).
	10	I1	-	-	1 in col. 10 indicates that each tile is at the same uniform temperature. 2 in Col. 10 indicates that each tile temperature distribution is governed by Lagrangian interpolation formulas. 3 in Col. 10 indicates that each tile temperature distribution is input by consecutive finite element node-temperature differences from the reference temperature.
	11-20	E10.0	T_{Ref}	^{o}F	Panel reference temperature (added to temp. differences when obtaining mat'l. properties)

F. TILE TEMPERATURE DISTRIBUTIONS — Sheet 2 of 2

CARD(S)	COL(S)	FORMAT	SYMBOLS	UNITS	DESCRIPTION
					UNIFORM TEMPERATURE OPTION (1)
F.2	1-10	E10-1	ΔT_u	F^o	Uniform temperature difference from T_{Ref}
					or LAGRANGIAN INTERPOLATION TEMPERATURE OPTION (2)
F.2.1	1-5	2I5	-	-	Number of x coordinates through which temperature differences will be interpolated.
	6-10		-	-	Order of Lagrangian interpolation polynominal in x direction. Must be at least 1 less than number of coords given in col. 5.
F.3.1	1-10	E10.0	x_i	in.	The local x coordinates used in the x direction temperature difference interpolation. Eight to a card until all are accounted fcr.
F.2.2-3.2					Repeat card types F.2.1 and F.3.1 for the y coordinates
F.2.3-3.3					Repeat card types F.2.1 and F.3.1 for the z coordinates
F.4	1-10 11-20 . . . 71-80	E10.0	ΔT_R	F^o	Successive interpolation point temperature, maximum of eight to a card. Start with the first x, y, z point and index on x. Next, step up y coordinate and index on x once again. Continue until all y coordinates have been stepped up in this way. Repeat the above procedure for each value of z: e.g., the temperature input order would be $T_1 = T(x_1, y_1, z_1)$, $T_2 = T(x_2, y_1, z_1)$, . . . $T_n = T(x_n, y_1, z_1)$, $T_{n+1} = T(x_1, y_2, z_1)$, . . . $T_{n+m} = T(x_n, y_m, z_1)$ $T_{n+m+1} = T(x_1, y_1, z_2)$, . . . , $T_{n+m+1} = T(x_n, y_m, z_\ell)$ Eight to a card until all data are accounted for.
					or ELEMENT NODE TEMPERATURE OPTION (3)
F.2	11-10 11-20 etc	E10.0	ΔT_R	F^o	Temperature differences above reference temperatures, node by node, in consecutive order. Seven temperature differences to a card until all nodes are accounted for. Cols. 71-80 of each card are reserved for user's card identification.

D. DESCRIPTION OF OUTPUT

Output from a typical run of the RESIST computer program is explained below in outline form. References in parentheses refer to pages in this Appendix. Refer to References 2 and 3 for sample problem output.

1. Program title and date indicating latest update of program version which was run.

INPUT INFORMATION

2. Listing of input cards, the first two of which are the title assigned to any given run by the user.

3. User selected input options are listed (pp. A-5 - A-8).

4. Plate, stringer and tile geometry and specification of finite element grids for primary structure and tiles (pp. A-9 - A-11).

5. Plate, stringer, strain isolator and arrestor material properties (pp. A-14 - A-17). Note, if there is no strain arrestor, RSI or isolator material properties may be used for the arrestor. If this is done, the thickness dimension of the usual isolator or RSI should be appropriately reduced to compensate for this addition.

6. Temperature-dependent RSI material property data used for generating curves used internally by program to compute RSI average finite element properties (pp. A-18 - A-19).

7. Plate and stringer boundary conditions (pp. A-20 - A-25).

8. Applied primary structure static mechanical and thermal loading if not a vibration problem (A-26 - A-27).

9. RSI temperature distribution input data. Used for property data (item 6 above) and thermal loading if a statics problem (pp. A-28 - A-29).

OUTPUT INFORMATION

10. Map showing typical tiles three dimensional finite element ordering, by layers. Top, or first layer also corresponds to two-dimensional tile coating elements as well.

11. Map showing ordering of a typical tiles finite element nodes by layers.

12. Position and temperatures for a typical tile in a local coordinate system (reference Figure A-4, A and B).

13. Global geometry of primary structure nodes and plate nodal degree-of-freedom numbering. D_x, D_y and D_z refer to nodal deflections, and R_x and R_y are the nodal rotations. Nodes with no degrees-of-freedom are used to define the stringer centroids for singly-attached stringers only.

14.a. Statics Option: Primary structure nodal deflections by iteration number. Nodes with the same x coordinate are grouped together. These groups are separated with dashed lines.

14.b. Vibration Option: Mode numbers, approximate frequencies and corresponding modal error bound (which should be less than 2% to be a reliable approximate mode). This is followed by the primary structure mode shapes with a similar nodal deflection format as for the Statics Option.

15. If requested by the user, the computed convergence parameter is printed out along with the input quantity it was tested against. This is done for each iteration after the first for the Static Option. The primary structure degree-of-freedom with the largest change from the previous iteration is also identified.

16. Tile nodal displacements by tile and iteration number. For a vibration option, this calculation and the subsequent ones are performed only for the user-specified vibration mode.

17. Modal mass associated with each tile for given mode is printed out as DEN.

18. Three dimensional tile stresses and strains for the bottom two layers of elements by element number. These quantities are computed at each element's 8 Gauss integration points. Gauss point stresses are believed to be more accurate than nodal values and provide more detail than simply the element's average stresses.

19. Three dimensional element average stresses and strains (by tile and iteration number).

20. Two-dimensional membrane element adhesive bond stresses. There are two bond layers, one on either side of the strain isolator. The numbers assigned to each bond element pair are identical and correspond to the three-dimensional strain isolator member sandwiched between them. The members of each pair are distinguished from one another by their z coordinates.

21. Two-dimensional membrane element coating stresses. Coating element numbers correspond to the three-dimensional element which they contact. The specific face which is involved in a coating strain and stress output may be identified by its coordinates. As many as four faces of a given three-dimensional element may have a coating. Examples of elements with 4, 3 and 2 coated faces are presented in Figure A-8. The order of the stress output for some of these elements, as well as the components involved, is shown on page A-33.

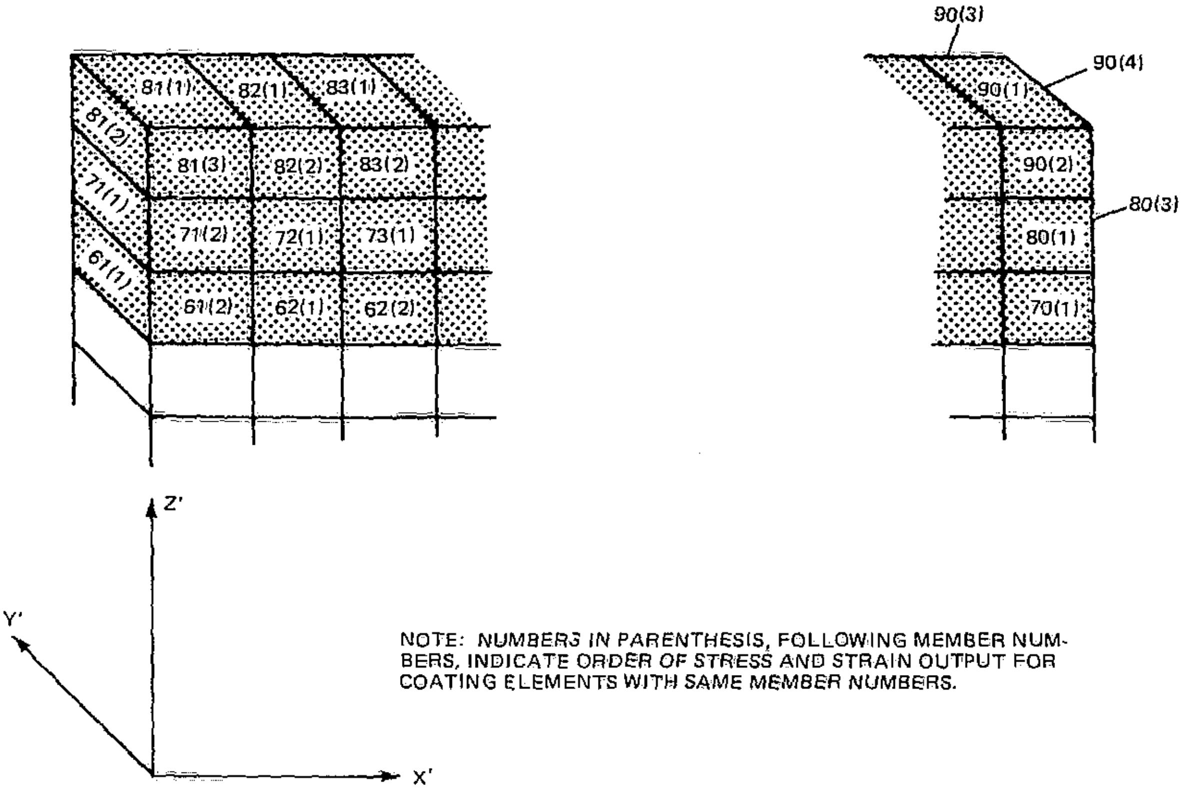
22a. Statics Option: Repeat of items 16-19 for each tile. Repeat of items 14.a and 15 for each iteration.

22b. Vibrations Option: Computation of Rayleigh Quotient (OMEGA SQUARED) if all tiles have been treated. Repeat of items 16-19 for each iteration. Repeat of items 14.b, 15 and Rayleigh Quotient until convergence or last iteration is performed.

23. Plate element stresses and strains for mid and/or top and/or bottom surfaces. This computation is done after each iteration if requested by the user. Otherwise, it is computed only after convergence or the last iteration is performed.

24. Vibrations Option: Stringer strains and stresses if requested in input, the quantity $(\sum_j A_{z_j} \bar{\phi}_{T,zj})^2$ (printed out as SUM (AREA * DZ)** 2=), and the primary structure modal mass (printed out as P.S. M =).

Members	Ordered output for Components of Stress
61(1)	yy, zz, yz
61(2)	xx, zz, zx
61(3)	xx, zz, zx
.	
.	
.	
73(1)	xx, zz, zx
73(2)	xx, zz, zx
.	
.	
.	
81(1)	xx, yy, xy
81(2)	yy, zz, yz
81(3)	xx, zz, zx
81(4)	xx, zz, zx
.	
.	
.	
90(1)	xx, yy, xy
90(2)	xx, zz, zx
90(3)	xx, zz, zx
90(4)	yy, zz, yz



NOTE: NUMBERS IN PARENTHESIS, FOLLOWING MEMBER NUMBERS, INDICATE ORDER OF STRESS AND STRAIN OUTPUT FOR COATING ELEMENTS WITH SAME MEMBER NUMBERS.

Figure A-8 Idealization with Coating Part-Way Down Sides of Tile