INERTIA RELIEF SOLUTIONS

OF

LARGE FINITE ELEMENT MODELS

WITH

APPLICATIONS OF MULTIPLE EXTERNAL SUPERELEMENTS

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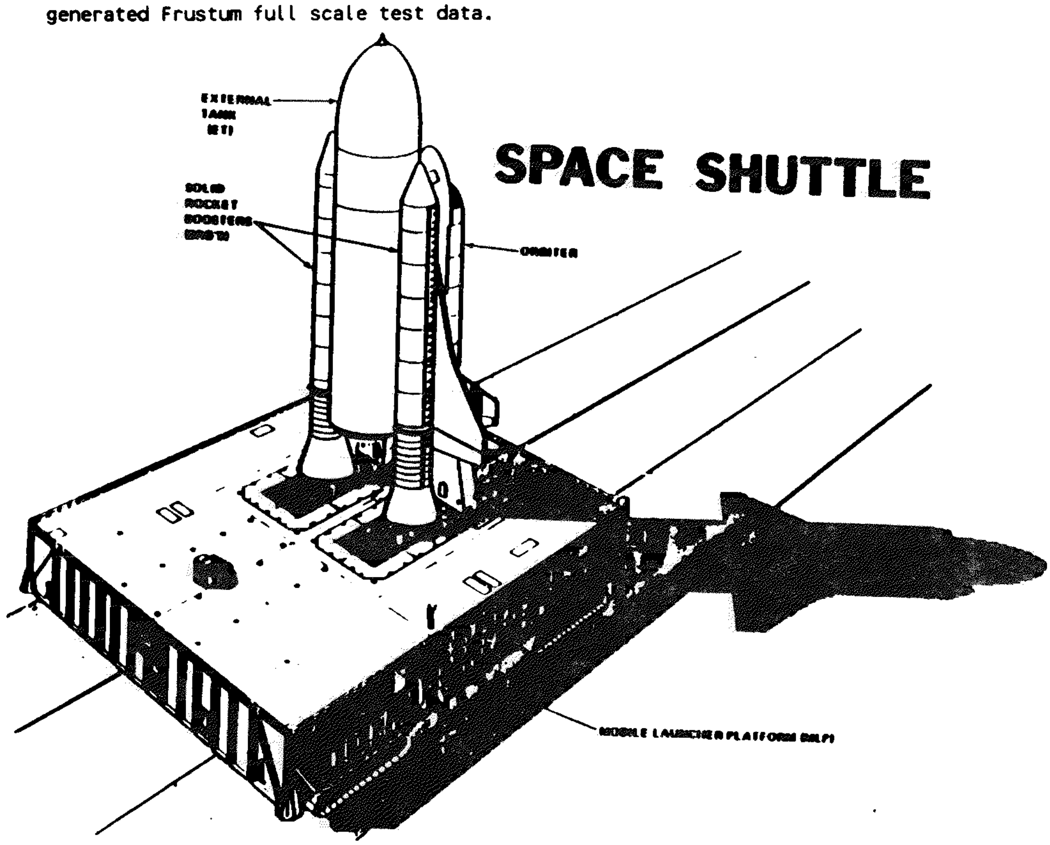
ABSTRACT:

The Space Shuttle Challenger accident triggered a complete recertification effort by NASA on all components of the Solid Rocket Booster (SRB). Stress analysis of the SRB components and assemblies was part of the recertification effort. The subject of this paper is the stress analysis of the Frustum. The analysis was accomplished by substructuring with the use of superelement (SE) techniques and inertia relief method of analysis as provided by MSC/NASTRAN Solution Sequences 61 and 91. The SRB Frustum is designed to provide housing for the forward separation motors which provide the thrust force to separate the SRB from the external tank at SRB burnout. It also provides support for the main parachutes, decelerating subsystem and nose cap thruster firing loads. The Frustum was divided into six (6) superelements (SE) of which five (5) were external (secondary). All external SE attached to the residual structure boundaries of the primary SE by means of the databases (DB) CSUPER cards and DMAP alters. Particular attention was paid to the output coordinate systems at the superelement interfaces. In summary the results of the analysis compared favorably with previously generated Frustum full scale test data.



I. GENERAL BACKGROUND

Following the Challenger accident, NASA required a complete recertification of all Solid Rocket Booster (SRB) components. Stress and structural analyses of the SRB components and assemblies were part of the recertification effort. The purpose of this paper is to present the stress analysis of the Frustum.

As a major structural assembly of the SRB, the Frustum is located forward of the Solid Rocket Motor/Forward Skirt/Ordnance Ring Assembly and aft of the Nose Cap (Figure 1). The SRB Frustum Structural Assembly is a riveted and bolted monocoque shell with seven (7) internal rings, five (5) shear beams and one (1) motor support beam for the Booster Separation Motor boxes (Figure 2). Two sets of intercostals provide stability during deployments of the parachutes (decelerator subsystems) and water impact.

The previous analysis employed relatively crude models which ignored the 8,000 plus fasteners and the change in the stiffness and mass during flight phases. The shear beams and intercostals were approximated with a minimal amount of bar and quad elements. These deficiencies resulted in the construction of a completely new 360 degree model with 20,000 plus grid points and 29,000 elements.

II. ANALYSIS APPROACH AND MODELING RATIONALE

The following parameters were governing factors in the development and analysis of the frustum global finite element model including all substructures.

1 - FLIGHT HISTORY

Figure 3 provides the sequence of events for the SRB from the time of separation (t = o) from the space shuttle orbiter and external tank through water impact (t $\cong$ 300 sec.).

2 - LOADING

The structure and loading environment determined the requirements for the finite element code. The loading required inertia relief with direct acceleration specification. Typical mass model input to MSC/NASTRAN is shown in Figure 5.

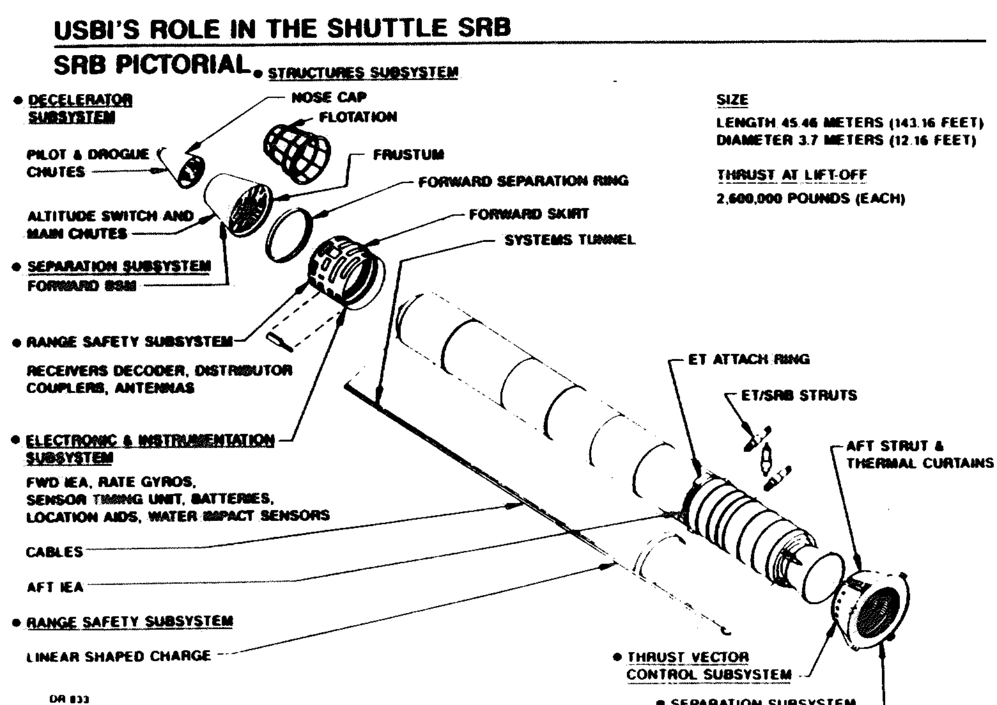


FIGURE 1

3 - FINITE ELEMENT DEVELOPMENT AND TECHNIQUES

In utilizing finite element analysis techniques on large complex structures, crucial modeling parameters such as mesh density, interface regions, boundary condition, etc., require special attention. In the FEM development of the SRB frustum model removal of certain components, due to SRB configuration changes during flight, dictated substructuring. Substructuring was accomplished with the use of external superelements (SE) and DMAP alters.

The frustum was divided into six (6) SE of which five (5) would be externals. Particular attention was given to the boundaries between the external superelements so they would be as independent of the loading sequence of the other SE's as possible. This would allow the use of a previously generated SE data base (DBXX) for part or all of the flight phases. The primary SE was a 180 degree model of the frustum (SE30/0). The forward skirt (SE50) was represented as a unique multilevel external SE. Other externals were the Isogrid (SE40), Booster Separation Motor Boxes (SE60 & SE70) and a 180 degree mirror image of the primary frustum (SE80). (See Figures 5 and 6 and Table 1.)

The external SE's attached to the residual structure boundaries of the primary SE (SE30/0). The interface regions between the frustum structural components and the external boundaries were handled by coincident gridpoints and CELAS2 elements. Major bolted connections employed CELAS2 elements with axial stiffness and CELAS2 elements with combined translational and shear stiffnesses. Bolt stiffness distribution factors also were generated based on the elastic bolt group analysis.

To avoid rigid body modes and to insure proper load transfer, particular attention was given to the coincident gridpoint output coordinate systems and ID assignments at the superelement interfaces.

4 - ANALYSIS

The analysis was completed with the use of MSC/NASTRAN solution sequences 61 STATICS and 91 INERTIA RELIEF. Specific criteria were applied during the development and analysis of the model for enforcing an effective and improving analysis process. The most important points of the criteria were:

- Development of a frustum pilot model to evaluate, anticipate, and study the global finite element model behavior. The behavior included but was not limited to applied loads, superelement techniques (external images and primary configurations), solutions and restart/data base methods.

- Mandate SPCFORCE balance, correct OLOAD results. Correcting output coordinate system errors to bring strain energy and epsilon values to within an acceptable range.

Databases were the vehicles used to connect the externals to the primary SE. DMAP alters wrote the required structural matrices to the individual SE databases. The databases, 4 to 5, were accessed with the use of CSUPER cards, PARAM cards and database keywords on the NASTRAN card. A typical data base arrangement for individual external SE's and residual/primary SE is provided in Appendix B. Application of MSC/NASTRAN solution 91 (SUPERELEMENT STATICS WITH INERTIA RELIEF), as provided in Appendix C in detail, assumes the structure is unsupported for some or all rigid body motions. Applied loads will cause acceleration of these rigid body modes of motion. This principle would correspond to the loading history of the frustum during its flight life with few exceptions. Figure 4 shows a system of mass inputs and four booster separation motors firing loads of 47,500 pounds each at both top and bottom locations along with corresponding mass moment of inertias. Inertia relief forces result from the mass distribution of the model shown which will balance the applied loads exactly. In other load cases such as re-entry of the SRB through the atmosphere, a direct acceleration of 8.5g horizontal and 4.0g vertical were applied along with other applicable aerodynamic loads. Rigid body checks on the conditioning of the matrices were checked against epsilon and strain energy calculations for KLR and KLL data blocks of the residual structure.

Postprocessing was done with the use of PATRAN with the aid of an in-house data translator program. The PATRAN translation program NASPAT would not correctly translate the superelement results for elements on the boundary between the residual structure and the primary superelement. PATRAN plots of individual components and superelements for the Booster Separation Motor Firing Load Case are included in Appendix A.

SRB FRUSTUM WITH DROGUE PARACHUTE

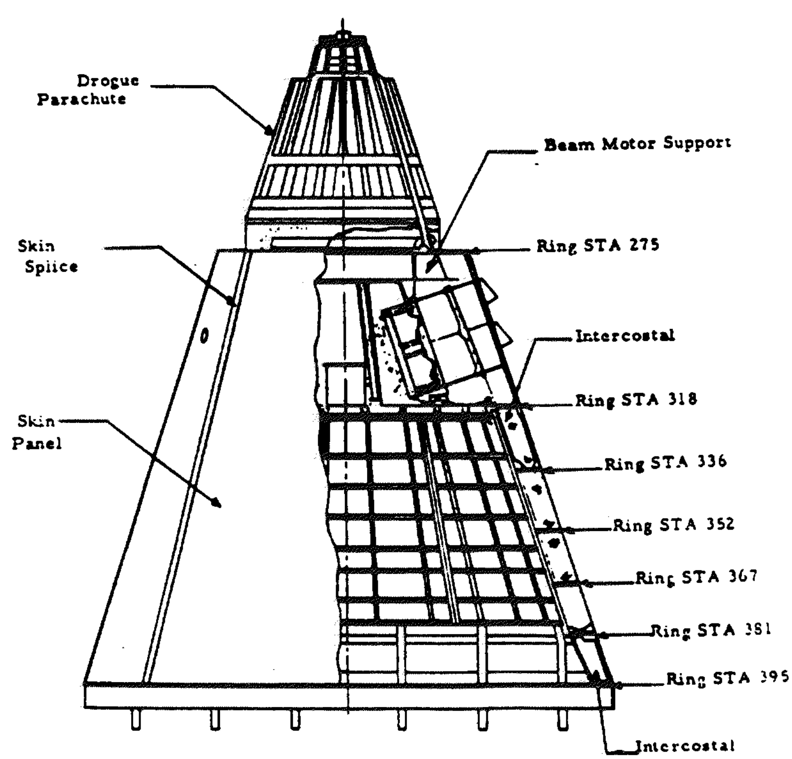


FIGURE 2

5 - CONCLUSIONS

Superelement techniques were applied for several reasons. This approach analyzed the complete frustum assembly including the interface regions between the superelements. It also allowed the task to be completed within the time and flight schedule constraints without compromising the technical complexity of the analysis. Accurate distribution of the mass properties and realistic representation of the load paths through the frustum were accomplished with the inertia relief solution techniques. In brief, the intention of this article is to demonstrate that in large finite element models of structures, where partitioning and coordination of the task is feasible, it is practical and advantageous to use superelement techniques where each partitioned segment (superelement) can be checked out and verified independently before it is assembled into a system of substructures. In general, air frame type structures can be analyzed using the inertia relief method of analysis.

Trajectory & Sequence

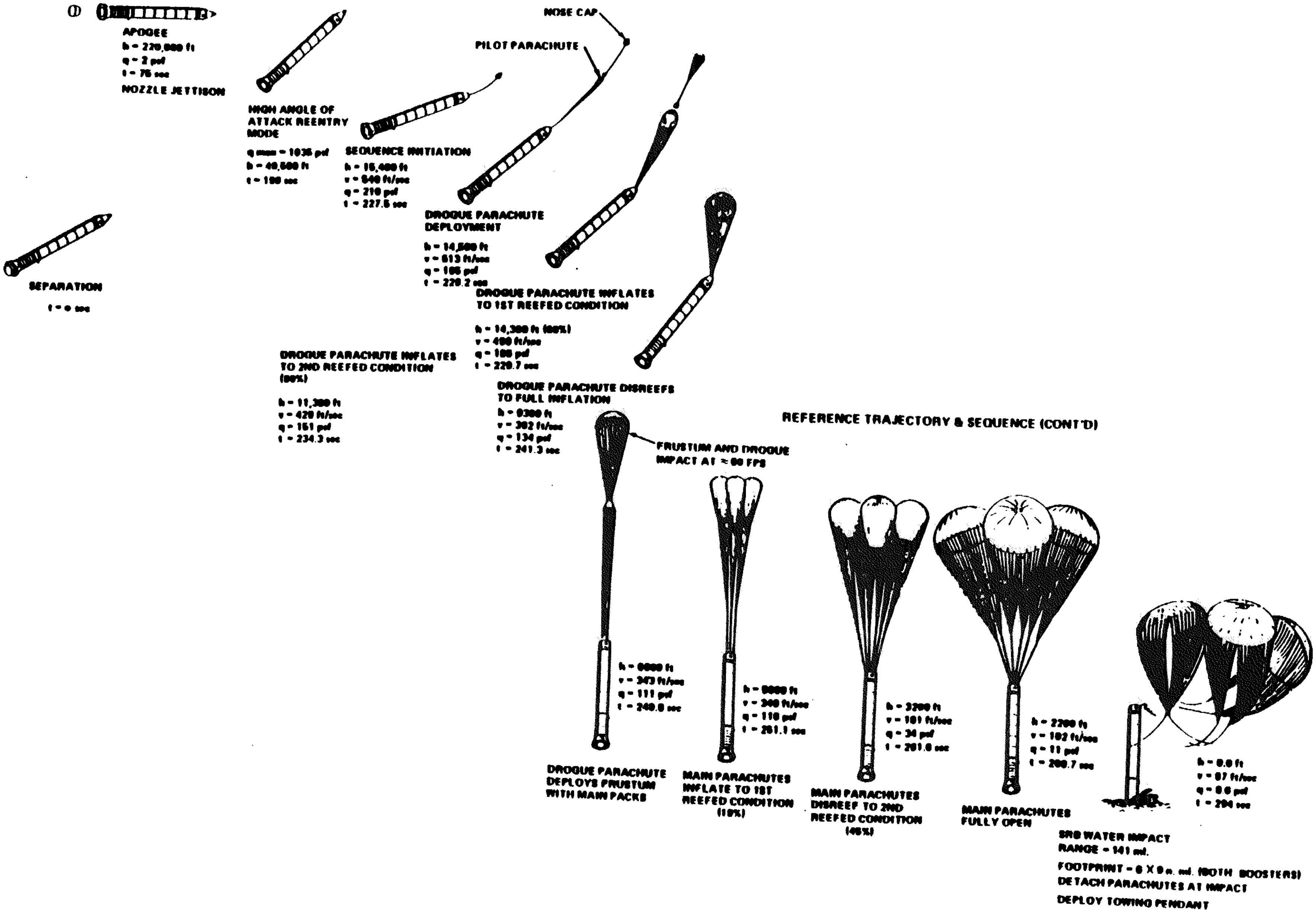


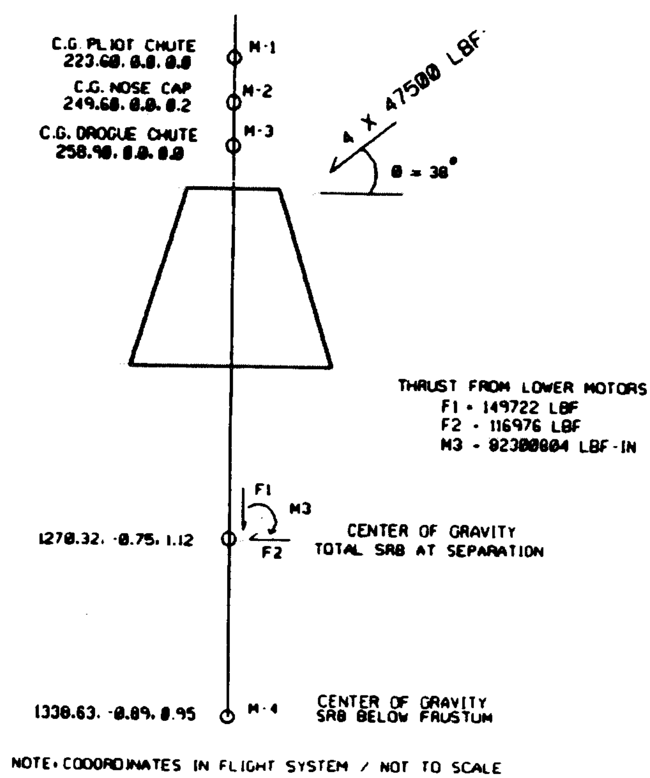
FIGURE 3

TABLE 1

FRUSTUM STATISTICS

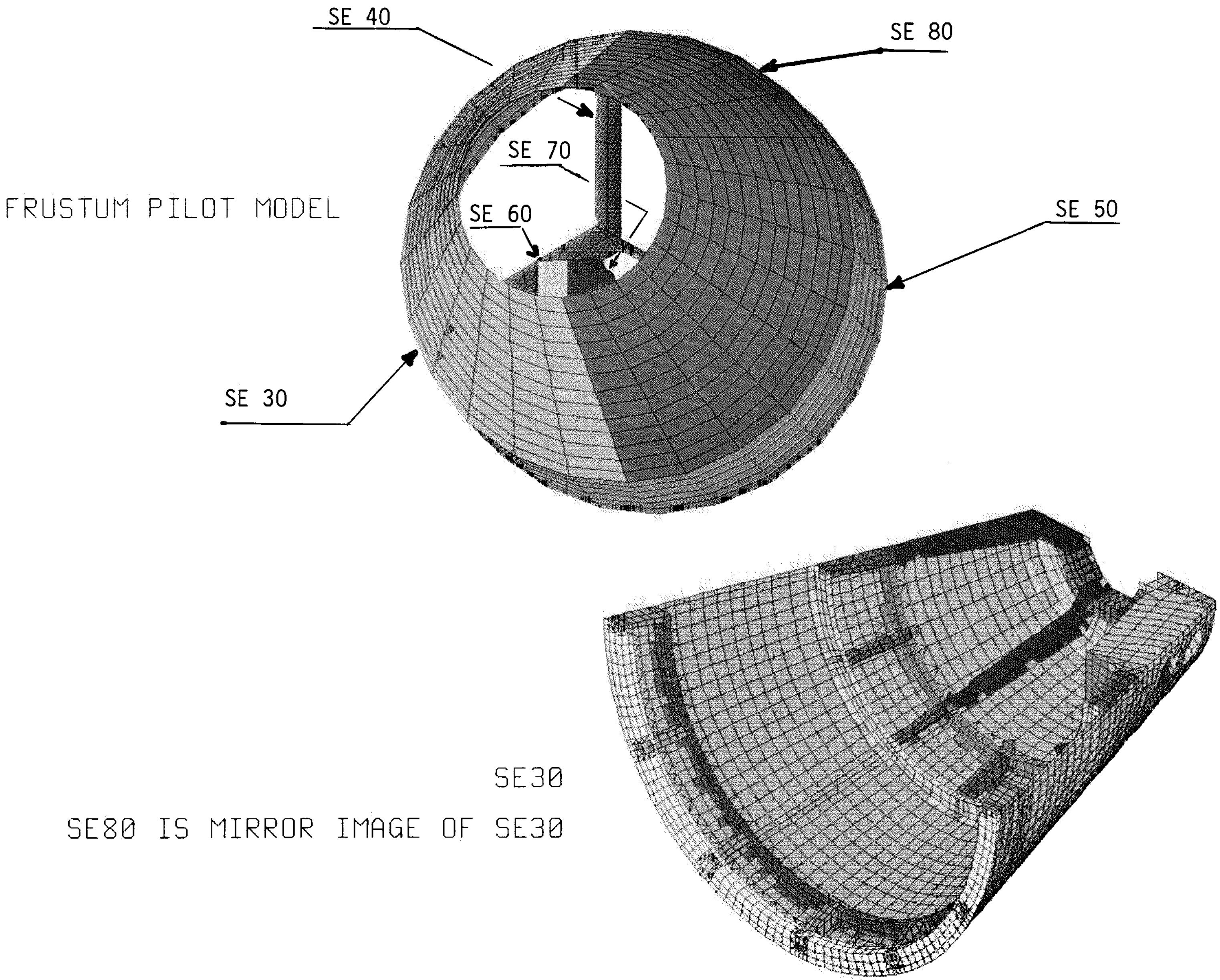
PRIMARY 180^{o} FRUSTUM (SE30/0)	6448 GRID POINTS	3795 CELAS2 6121 CQUAD4 926 CTRIA3 282 BAR
ISOGRID SUBASSEMBLY (SE40)	1145 GRID POINTS	681 CQUAD4 51 CTRIA3 594 BAR
FORWARD SKIRT 360^{o} (SE50)	3697 GRID POINTS	3360 CQUAD4
PRIMARY BSM BOX (SE60)	1462 GRID POINTS	1327 CQUAD4 126 CTRIA3 164 BAR
IMAGE BSM BOX (SE70)	1462 GRID POINTS	1327 CQUAD4 126 CTRIA3 164 BAR
IMAGE 180^{o} FRUSTUM (SE80)	6061 GRID POINTS	3177 CELAS2 5611 CQUAD4 849 CTRIA4 274 BAR
TOTAL	20275 GRID POINTS	28955 ELEMENTS

	WEIGHT POUNDS	CENTER OF GRAVITY Station-Inches			MOMENT OF INERTIA Slug-Ft^2 x 10-6			PRODUCT OF INERTIA Slug-Ft^2 x 10-6		
		X	Y	Z	IX	IY	IZ	IXY	IXZ	IYZ
M-1	-42.0	223.60	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
M-2	-310.4	249.60	-0.10	0.20	0.000040	0.000052	0.000052	0.000000	0.000000	0.000000
M-3	-1252.0	258.90	0.00	0.00	0.000090	0.000083	0.000083	0.000000	0.000000	0.000000
M-4	176158.3	1338.63	-0.89	0.95	0.182560	9.261696	9.267248	-0.025823	0.006889	-0.000428



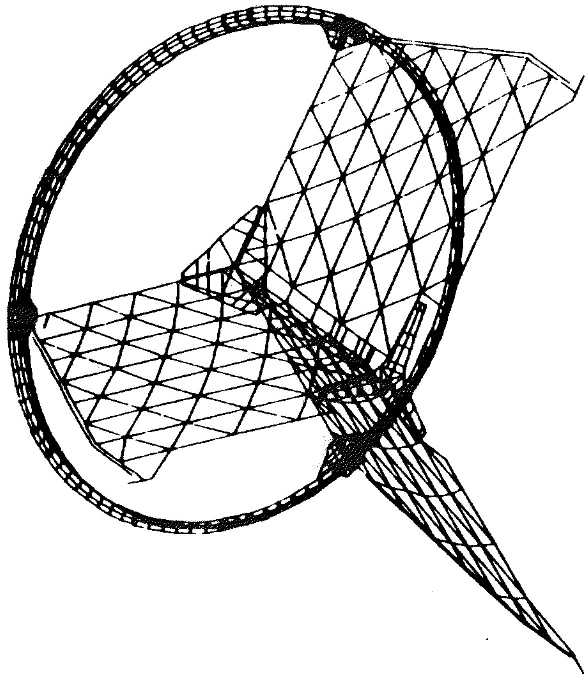
FREE BODY DIAGRAM FOR BOOSTER
SEPARATION LOAD CASE.

FIGURE 4



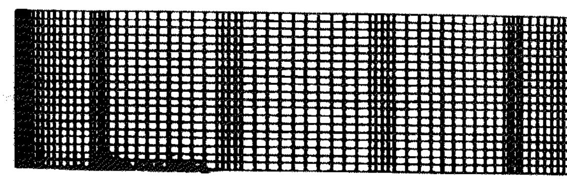
FRUSTUM PILOT MODEL
SE 40
SE 80
SE 70
SE 60
SE 50
SE 30
SE30
SE80 IS MIRROR IMAGE OF SE30

FIGURE 5

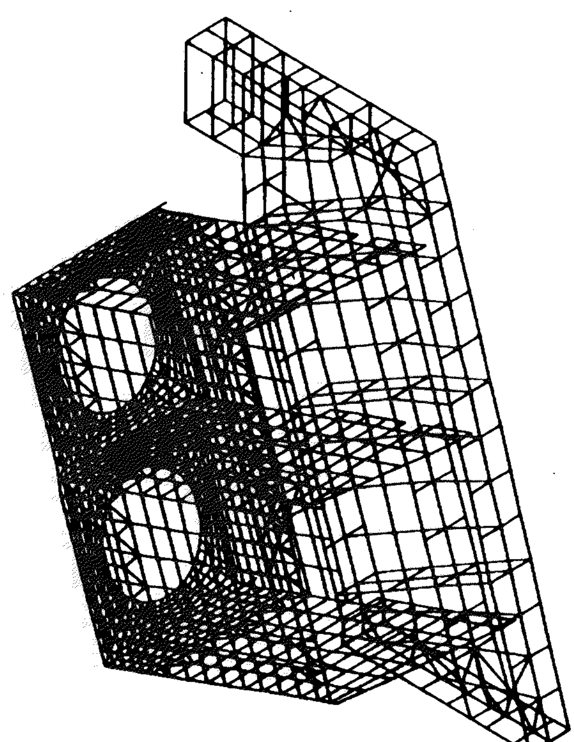


MAIN PARACHUTE SUPPORT STRUCTURE

SUPERELEMENT 40



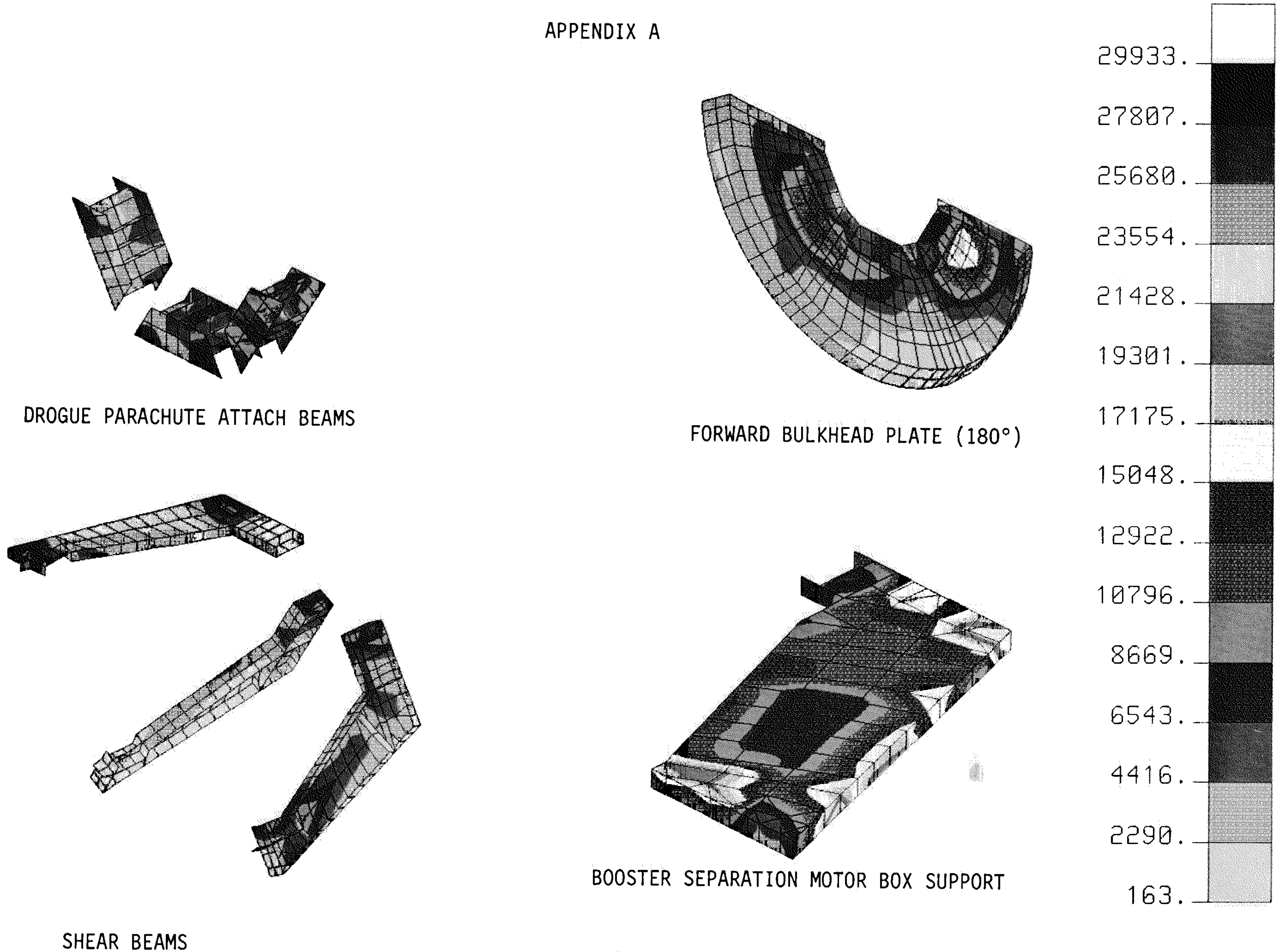
SUPERELEMENT 50



TITLE : SUPERELEMENT 60 (IMAGE 70)

FIGURE 6

APPENDIX A



VON MISES STRESS CONTOUR PLOTS
BOOSTER SEPARATION MOTORS FIRING LOAD CASE FOR FRUSTUM SE30 COMPONENTS

APPENDIX B

NASTRAN SYSTEM PARAMETER ECHO

```
NASTRAN SYSTEM(34)=200000  $  MAXIMUM SIZE FOR INTERNAL SCRATCH FILES
NASTRAN SYSTEM(105)=1         $ ASSIGN SCRATCH FILES TO SSD
NASTRAN BUFFSIZE=9217,DBSET 1=(DBO1,DBO2),
DBSET 2=(DBO3)
```

TYPICAL EXTERNAL SUPERELEMENT DATA BASE GENERATION (DBSET 2 CONTAINS REDUCED DATA OF EACH EXTERNAL SE)

```
ID REV,ISOEXT
TIME 10000
SOL 91
ALTER 8,8
DBMGR //O//V,Y,DBNBLK=6000/////DBO1 $
DBMGR //O//V,Y,DBNBLK/////DBO2 $
DBMGR //O//V,Y,DBNBLK/////DBO3 $
DBMGR //2 $
$
$ THIS ALTER WILL CAUSE THE SEMAP TO BE PRINTED
$ ALONG WITH THE CSUPER CARD BEING PUNCHED.
$ SEE PARAM SEMAPOPT AND SEMAPPRT BELOW IN BULK DATA.
$
ALTER 79
TABPRT    EMAP,ESTDATA,TIMSIZ//V,Y,KEY=SEMAP/V,Y,OPT1=42/
          V,Y,OPT2=3/ DMAPNO  $
ALTER 866
DBFETCH /KAA,KLAA,BAA,K4AA,EQEXINS/V,Y,MODEL=O/V,Y,SEIDEXT//+1 $
DBFETCH /MAA,MLAA,PA,,/MODEL /SEIDEXT //+1 $
DBSTORE KAA,KLAA,BAA,K4AA,EQEXINS //MODEL /SEIDEXT /+2 $
DBSTORE MAA,MLAA,PA,, //MODEL /SEIDEXT /+2 $
DBMGR  //2 $
ENDALTER
CEND
```

TYPICAL RESIDUAL SUPERELEMENT DATA BASE GENERATION

NOTE: DBSET 15 IS READ ONLY DATA BASE. (ALL THE EXTERNAL SE'S REDUCED DATA ARE READ INTO THE DBSET 15)

```
NASTRAN BUFFSIZE=9217,DBSET 1=(DBO1,DBO7,DBO8),
DBSET 15=(DBO2,DBO3,DBO6)
ID FRUSTUM,PRIME
TIME 90000
SOL 91
$ PATRAN POST PROCESSING ALTER
$ SOLUTION 91 SUPERELEMENT STATICS
ALTER      1 $
OUTPUT2    ,,,,//C,N,-1/C,N,11/V,N,Z $
ALTER 8,8
DBMGR //2 $
DBMGR //O//V,Y,DBNBLK=16000/////DBO1 $
DBMGR //O//V,Y,DBNBLK/////DBO7 $
DBMGR //O//V,Y,DBNBLK/////DBO8 $
ALTER      714 $
VECPLOT    UGVS,BGPDTS,EQEXINS,CSTMS,CASEDR,/UGVBASIC//O/1 $
SDR2       CASEDR,CSTMS,MPT,DIT,EQEXINS,,,,BGPDTS,,,
           UGVBASIC,,/,,OUGV1PAT,,,/STATICS/S,N,NOSORT2/
           V,N,NOCOMP $
OUTPUT2    OUGV1PAT,OES1//O/11/V,N,Z $
$ END OF PATRAN ALTER
ALTER 815
DBMGR //2 $
CEND
$
SEALL=ALL
$
SUPER = ALL
$
```

APPENDIX C

INERTIA RELIEF METHOD OF ANALYSIS

BACKGROUND: Generally in analysis with inertia relief, the structure is assumed to be unsupported for some or all rigid body motions. Applied loads will cause acceleration of these rigid body modes of motion (if their resultant are non zero). Inertia relief results from computing the inertial loads due to the mass distribution of the model that will balance the applied loads exactly. An application might be the steady-state loads in an air frame during a steady turn after all of the dynamic transients have attenuated.

METHOD OF ANALYSIS & NASTRAN OPERATION:

One grid point is used as the reference point for the entire model (exterior to all superelements and interior to residual structure). Prescribed rigid body accelerations are possible to input through the reference grid point.

1 - Conventional stiffness matrix and mass (M_{jj}) matrix as well as generation of the load vectors are performed.

2 - The usual reduction of the stiffness matrix to the boundry stiffness matrix is performed.

3 - Reduction of load vectors produces the following qualities:

$\{Q_r\}$ - Load Resultant (NASTRAN, QRL) 6 x I Matrix where I = No. of Loadcases

$\{P_o^s\}$ - Loads on omitted points

$\{P_s^s\}$ - Loads on single-point constraints

$\{P_a\}$ - Reduced Loads

$\{P_l\}$ - Loads on leftover points

a) The rigid body transformation matrix $[D_{gr}]$ is generated (VECPLOT Module). Its columns contain the motion of all degrees of freedom due to unit motion of corresponding reference point degree of freedom.

b) Unit loads due to rigid body accelerations are computed.

$$[P_{jr}] = -[M_{jj}][D_{gr}]$$

c) For downstream superelement only, the unit load vectors are summed (SELA Module)

$$[P_{gr}] = [P_{jr}] + \Sigma_i \, [P_{ar}]$$

d) The unit loads are reduced by the conventional SSG2 module to produce.

$[Q_{rr}]$ - Reactions to unit loads (6 x 6 Matrix)

$[P_{or}]$ - Loads on omitted points

$[P_{sr}]$ - Loads on constrained points

$[P_{ar}]$ - Reduced loads

$[P_{lr}]$ - Leftover loads