Nonlinear analysis of Ariane-5 engine frame

D. Vandepitte / E. Riks
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of Ariane 5 engine frame

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March 18, 1992
Abstract

The Ariane 5 engine frame (Bâti Moteur Équipé BME) is subjected to a complicated series of load cases. Conventional design and verification analyses with finite element models implicitly adopt a linear approach. Structural deformations are small and material behaviour remains within the elastic domain. For small load magnitudes, a linear approach is acceptable. The structure is a thin-walled light-weight structure subjected mainly to compressive loading. At certain load levels, the linear approach is no longer appropriate.

When large structural deformations occur, load paths probably change. A thin-walled shell that is subjected to in-plane loading is loaded also by bending moments. At certain load levels, the structure is expected to collapse, due to a combined effect of geometric and material nonlinearities. Nonlinear behaviour is studied with a load incrementation algorithm.

This analysis does not take into account local buckling. These effects are appropriately covered with simple formulas. Local buckling does not lead to collapse of the structure. It only affects structural stiffness of the shell that is stiffened with stringers. Nonlinear effects that are studied here necessarily involve structural deformations of portions of the structure that are wider than the stiffener pitch. In order for the structural design to be sound, the margin of safety with respect to general instability should be clearly beyond margins for local buckling.

Some portions of the structure are sensitive to nonlinear behaviour, some other portions are not. The finite element model that is prepared for nonlinear analysis is bound to meet certain requirements in order to appropriately describe nonlinear behaviour. Some assumptions on how the structure is expected to respond are necessary. Due to the complexity of the problem on the one hand and to computer hardware limitations on the other hand, specific assumptions are made on symmetry of both structure and loading. Wherever necessary, assumptions are conservative.

In the baseline load case, only motor load is applied. Secondary load cases involve other major load components. They all lead to a similar collapse mode. Corresponding load levels are yet significantly different. Margins of safety with respect to general panel buckling ($MS>2$) are sufficiently greater than the margin of safety with respect to local buckling ($MS\approx 0.2$). Structural collapse is due to exceedance of the material yield stress.
Contents

1 Introduction ........................................... 8

2 Referenced documents and drawings .................. 10

3 Description of the engine support and analysis objectives .................. 12
   3.1 Basic design features .................................. 12
       3.1.1 The cross assembly ................................ 13
       3.1.2 The cone assembly ................................ 13
       3.1.3 The box assembly ................................ 15
   3.2 Loads on the engine frame ............................. 16
       3.2.1 Primary load cases ................................ 17
       3.2.2 Secondary load cases ................................ 17
   3.3 Objectives of the analysis ............................. 19
       3.3.1 The notion of the collapse load .................. 19
       3.3.2 Buckling and bifurcation .......................... 20
       3.3.3 Multi-parametric loading .......................... 21
       3.3.4 Objective of the analysis .......................... 21
   3.4 Selection of the worst load cases .................... 22

4 Availability of computational tools .................... 24
   4.1 MSC/NASTRAN for nonlinear analysis ................. 24
       4.1.1 Selection of MSC/NASTRAN ......................... 24
       4.1.2 Implementation of the nonlinear solution procedure .. 25
   4.2 The computer environment ............................. 26
CONTENTS

4.3 Basic restrictions .................................................. 27
  4.3.1 Computer capacity limitations ............................ 27
  4.3.2 MSC/NASTRAN code limitations ......................... 28

5 Modelling considerations ...................................... 30
  5.1 General approach .............................................. 30
    5.1.1 The ideal model ........................................ 30
    5.1.2 Regularity conditions .................................. 31
    5.1.3 Simplifications ........................................ 31
  5.2 Constraints for the modelling of stiffeners ............. 32
  5.3 Modelling rules and conventions ......................... 33
    5.3.1 The cross assembly .................................... 33
    5.3.2 The cone assembly ..................................... 34
    5.3.3 The box assembly ..................................... 37
  5.4 Material properties ........................................ 39

6 Computations and basic results .............................. 43
  6.1 Preliminary analyses ...................................... 43
    6.1.1 Sample problems ...................................... 43
    6.1.2 Coarse grid model engine frame ....................... 44
  6.2 Results for the 90° model ................................ 44
  6.3 Results for the 180° model ................................ 46
    6.3.1 Load case EPSYAH .................................... 46
    6.3.2 Load case EPSYAH130 ................................ 48
    6.3.3 Load case VROOA ..................................... 50
    6.3.4 Load case EPSYAHVAO ................................. 55
    6.3.5 Load case VROOA130 .................................. 62
    6.3.6 Summary of results .................................. 64
    6.3.7 Some additional comments ............................. 66
  6.4 Interpretation of results ................................ 67
    6.4.1 Reliability of the finite element computations .. 67
CONTENTS

6.4.2 Evaluation of the collapse load ........................................... 68

7 Conclusion ................................................................. 70

A Model characteristics .................................................. 71
   A.1 Model Qv5 .......................................................... 71
   A.2 Model Bc2 .......................................................... 74
   A.3 Model Bcc .......................................................... 76

B Coordinate systems .................................................... 79
   B.1 General considerations ........................................... 79
   B.2 List of spherical coordinate systems ........................... 80
   B.3 List of cylindrical coordinate systems ....................... 82
   B.4 List of rectangular coordinate systems ...................... 84

C Conventions in node and element numbering .................... 85
   C.1 Node numbering .................................................. 85
   C.2 Element and property numbering ................................ 87

D Parameter settings in MSC/NASTRAN .............................. 89
   D.1 Incremental nonlinear procedures ............................. 89
   D.2 Path following procedures ................................... 91
   D.3 Material properties ............................................ 91
List of Figures

1.1 Load–displacement curve in linear vs. nonlinear analysis ................. 8
3.1 Unflanged stiffener section ........................................ 14
3.2 Excentric panels' neutral axes ..................................... 14
3.3 Cone - cross connection design ..................................... 15
3.4 Box - cone lap joint design ......................................... 15
3.5 Box floor design .................................................... 16
3.6 Box cylinder wall design ........................................... 16
3.7 Load–displacement curve in linear vs. nonlinear analysis: softening and hardening response ........................................ 20
5.1 Bending of unflanged stiffeners ..................................... 32
5.2 Conservative modelling of unflanged stiffener section ............... 33
5.3 Modelling of cone panel offsets .................................... 35
5.4 Cone - cross connection model ...................................... 36
5.5 Box - cone lap joint model .......................................... 37
5.6 Modelling of ring frame cross-sections ............................. 38
5.7 Model of the box floor ................................................ 38
5.8 Model of box cylinder wall .......................................... 39
5.9 Modelled material behaviour at room temperature .................. 41
5.10 Modelled material behaviour at 130°C ............................ 42
6.1 Load–displacement curve for model Qu5 ................................ 45
6.2 Collapse mode for model Qu5, \( MS = 3.49 \) ............................ 47
6.3 Load–displacement curve for load case EPSYAH .................... 49
LIST OF FIGURES

6.4 Collapse mode for load case EPSYAH, $M_S = 3.335$ .......................... 49
6.5 Load–displacement curve for load case EPSYAH130 ............................ 51
6.6 Collapse mode for load case EPSYAH130, $M_S = 2.684$ ........................ 51
6.7 Load–displacement curve for load case VROOH ................................. 54
6.8 Collapse mode for load case VROOH, $M_S = 2.123$ ............................ 54
6.9 Load–displacement curve for load case EPSYAHVAO ............................ 61
6.10 Collapse mode for load case EPSYAHVAO, $M_S = 3.293$ ...................... 61
6.11 Load–displacement curve for load case VROOH130 ............................ 65
6.12 Collapse mode for load case VROOH130, $M_S = 1.625$ ...................... 65
6.13 Load–displacement curves for all load cases ................................. 66

A.1 Model QU5 mesh .......................................................... 72
A.2 Model BC2 mesh .......................................................... 75
A.3 Model BCC mesh .......................................................... 77
List of Tables

3.1 Loads on LOX on cone in load case "allumage, décollage, vent et rafale" 18
3.2 Loads on LOX on cone in unnamed load cases ............................... 18
3.3 LBS disconnection loads .......................................................... 19
3.4 Loads at successive flight events .................................................. 19
3.5 List of load cases that are considered in nonlinear analysis .............. 23

5.1 Tensile and compressive yield stresses of AL7075-T7351 at room temperature ................................................................. 40

6.1 Load incrementation scheme for load case EPSYAH ....................... 46
6.2 Modified load incrementation scheme for load case EPSYAH .......... 48
6.3 Load incrementation scheme for load case EPSYAH130 .................. 50
6.4 Modified load incrementation scheme for load case EPSYAH130 ....... 52
6.5 Load incrementation scheme for load case VROOAH .................... 53
6.6 Modified load incrementation scheme for load case VROOAH .......... 53
6.7 Load cases for preliminary linear analysis DEROAH 3.0 s .............. 57
6.8 Load cases for preliminary linear analysis VROOAH 75.5 s ........... 57
6.9 Load cases for preliminary linear analysis EPSYAH 107 s ............ 57
6.10 Load cases for preliminary linear analysis EPDIATI 118.5 s .......... 58
6.11 Displacements for load cases group 10, DEROAH 3 s .................. 58
6.12 Displacements for load cases group 20, VROOAH 75.5 s ............ 59
6.13 Displacements for load cases group 30, EPSYAH 107 s .............. 59
6.14 Displacements for load cases group 40, EPDIATI 118.5 s ........... 59
6.15 Load incrementation scheme for load case EPSYAH VAO .............. 60
<table>
<thead>
<tr>
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<tr>
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<td>Load incrementation scheme for load case <strong>VROOAH130</strong></td>
<td>63</td>
</tr>
<tr>
<td>6.18</td>
<td>Modified load incrementation scheme for load case <strong>VROOAH130</strong></td>
<td>63</td>
</tr>
<tr>
<td>6.19</td>
<td>Summary of margins of safety</td>
<td>64</td>
</tr>
<tr>
<td>A.1</td>
<td>Model properties <strong>QU5</strong></td>
<td>73</td>
</tr>
<tr>
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<td>74</td>
</tr>
<tr>
<td>A.3</td>
<td>Model properties <strong>BCC</strong></td>
<td>78</td>
</tr>
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</table>
Chapter 1

Introduction

The Bâti-Moteur Équipé of the Ariane 5 main stage transfers engine thrust to the launcher's first stage. The engine frame's components are loaded mainly in compression. A buckling and collapse analysis is necessary in order to investigate the structure's stability. Its basic geometry is a ring and stringer stiffened conical shell. Due to design requirements, however, it features many complex geometrical details. The structure's complicated response to compressive loading can not be predicted with theoretical formulas. Even the assumption of a constant meridional cross-section is not feasible due to geometrical irregularities of the structure.

Conventional finite element modelling adopts linear structural behaviour. All computations that were performed at Fokker Space & Systems BV likewise assume a perfectly linear relationship between load and response. At certain load levels, however, this assumption is no longer valid. Nonlinear structural behaviour may be due to geometrically large deformations or to material nonlinearity. Both effects cause the load-displacement curve to deflect from a straight line (fig 1.1). The structure's stiffness decreases there

![Graph showing linear and nonlinear analysis](image)

*Figure 1.1: Load-displacement curve in linear vs. nonlinear analysis*

with increased loading. The present study is done to reveal the load levels where non-
linear effects start to appear.

The final result of this investigation is a collapse load level and the corresponding collapse mode. Several load cases have to be considered separately because nonlinear analysis does not allow linear superposition. One particular load case will be most critical.
Chapter 2

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Chapter 3

Description of the engine support and analysis objectives

This study focuses on the nonlinear behaviour of the engine frame that is loaded in compression. This consideration is the driving factor when selecting modelling options.

3.1 Basic design features

The structure largely consists of four major assemblies:

- the cross assembly transfers the engine thrust’s point load to a circularly distributed load at the bottom of the cone, the load distribution still exhibits some clearly pronounced peaks at the cross webs

- the cone assembly transfers an unequally distributed compressive load to the upper structure where the load distribution is much smoother; the cone assembly is loaded primarily by membrane forces

- the box assembly redirects membrane loads in the cone panels to vertical loads which are then transferred to the launcher’s first stage; this component features a closed box structure which is capable of handling bending and torsional moments

- the LBS assembly (Liaison Bord Sol) is not a structural load carrying component after take-off; it merely serves as a connection for filling the launcher’s fuel tanks with liquid propellant and for providing power before take-off; significant loading occurs only at take-off when connections between the launcher and the launch platform are broken by sudden rupture

Each assembly has a clearly distinct role to play in the transfers of engine thrust. Not all assemblies are as critical. Modelling considerations differ for each assembly.
The entire structure is made of Aluminum AL7075-T7351. Homogeneous material properties are assumed, and the material is supposed to be isotropic. Basic material properties are derived for original plate thickness equal to 50 mm.

3.1.1 The cross assembly

Engine thrust is applied as a point load at the bottom of the cross assembly. It is transformed to an irregularly distributed perimeter load at the top of the cross assembly. This structure basically acts as a very stiff column that transfers engine thrust to two perpendicular, large beams. These beams are loaded in bending. None of the cross assembly’s components is expected to exhibit significantly nonlinear behaviour, at engine thrust levels which exceed limit load by a factor of 5 to 10. For this reason, the cross assembly should not be included in the model of the engine frame.

3.1.2 The cone assembly

The cone assembly is a thin-walled shell with ring and stringer stiffeners. It is very stiff in the transfer of membrane forces. It possesses only little stiffness in the transverse direction perpendicular to the cone panels’ tangent plane. Bending moments in the circumferential direction cause rather large deflections to occur. The cone assembly is expected to behave in a particularly nonlinear way.

The cone panels feature some complex geometric details. Some of them have to be incorporated in the model in order to describe possible buckling phenomena. As a general rule, locals details that are considered to be important for the nonlinear behaviour of the structure are included. Less important features are left out. Wherever necessary, a conservative approach is adopted:

- panels’ unflanged stiffeners have a constant height of 38 mm; their thicknesses however, vary from 2.1 mm to 5.0 mm
- panels and stiffeners are milled from a uniform plate with constant thickness of 50 mm, the radius at the root of the stiffener is 3.2 mm (fig. 3.1, scale 1/1);
- panels’ thicknesses vary throughout the entire cone; it is required that their variation is modelled accurately
- apart of the fact that panels are curved, their outer faces are perfectly flat, i.e. variation in panels’ thicknesses are visible only from the interior of the cone; panels’ neutral planes are shifted a small amount at connections between different panel’s thicknesses (fig. 3.2); resulting offsets cause excentric load transfer and thus, bending moments
Figure 3.1: Unflanged stiffener section

Figure 3.2: Excentric panels’ neutral axes

- cone panels are connected to the cross assembly with a double row of bolts (see fig. 3.3)
- cone panels are connected to the box assembly with a triple row of bolts (see figure 3.4)
- due to design requirements, panels have holes; panel and stiffener thicknesses are increased at the edges of holes
- lap joints connect two panels with bolts; usually, individual panels have the same thickness as the surrounding panels
- cone panels are stiffened locally to smoothly introduce equipment loads; since VAO loads (Vanne d'Alimentation Oxygène) will be considered further, the LOX
beams are particularly important

- all other brackets are omitted, together with local equipment loads

All of these design features have some consequences on the actual modelling strategy. They determine the mesh density. This topic will be discussed in chapter 5.

### 3.1.3 The box assembly

The box assembly redirects membrane forces in the cone panels to vertical forces through the RIE interface (Réserveur Isolé Équipé). Consequently it is loaded by a combined effect of vertical forces and moments. It is designed as a closed box structure that consists of four major components.
the box floor is a circular ring in a horizontal plane; in the actual structure horizontal solid propellant booster loads are introduced into the engine frame; the floor is a stiffened plate with variable thickness and variable stiffener dimensions (fig. 3.5)

![Figure 3.5: Box floor design](image)

the box cylinder is formed as a flat panel with variable thickness and pockets of variable dimensions, which is curved after the pockets are milled to the correct dimensions (fig. 3.6):

![Figure 3.6: Box cylinder wall design](image)

- conical panels close the box at the inside; they are designed as conical shell with unflanged stiffeners; stiffeners are on the outside of the conical panels
- box radial webs are inside the triangular box, they connect the box floor to the cylinder wall and the conical panels in order to stiffen the cross-section of the box assembly; radial webs are distributed irregularly around the perimeter, they are concentrated around the solid booster bar attachments

### 3.2 Loads on the engine frame

The different load cycles that the structure is subjected to are described in specification documents ref. [1-3] and loads report ref. [4]. Many different load components are applied to the engine frame. Nonlinear analysis does not allow separate load cases to be superposed to each other. It will be hard to draw conclusions for one load case based
on results for another load case. Every load case that is considered to be important will have to be run separately.

### 3.2.1 Primary load cases

The major load that the engine frame is subjected to is engine thrust. Both actuators tilt the engine with respect to the longitudinal axis of the launcher. Engine thrust has components in three directions. Each of those components vary with time. Loads' time histories are prescribed by the technical specifications. Most critical loads occur when engine thrust is maximum. Maximum engine thrust is 1.167 MN in vertical direction. At the moment vertical engine thrust is maximum, horizontal load components are relatively small.

### 3.2.2 Secondary load cases

Next to engine thrust, other load components are active. Equipment loads, loads introduced by booster bars, liquid propellant fuel line loads, ... are applied to the structure according to a history specified in the load case report ref. [4].

The present study always focuses on maximum engine thrust as the baseline load case. Any other load component is considered only after the nonlinear effects caused by the baseline load case are thoroughly understood. Some of the secondary load cases will have significant nonlinear effects, some others will not. For each load case that is identified to be important, a margin of safety will result. The most critical nonlinear load case gives the lowest margin of safety.

The load case report ref. [4] lists the criteria that are used to identify separate load cases and to extract critical load cases. All load cases are given coded names expressing the instant of time and the flight conditions when they occur. For each case six different load components are identified:

- **motor loads**: engine thrust is obviously the primary load component. It is given together with transverse load components.

- **booster bar loads**: connection loads from the solid propellant boosters are applied to the engine frame via booster bars. These loads tend to deform circular cross-sections of the cone to a kind of oval shape. Radial components may be of the order of a few millimeters. It is expected, however, that deformations of such a small magnitude are not capable of changing the nonlinear behaviour of the structure considerably. This statement may be intuitive at this time, it will be proven to be valid when results are described.

- **quasi-static acceleration**: inertia effects are neglected
LOX on cone: loads are applied at the connection LOX on cone (VAO), five distinct cases of loading on LOX-line are identified:

1. “attente avant tir”
2. “allumage, décollage, vent et rafale” (see table 3.1). Any combination of these numbers can occur.

<table>
<thead>
<tr>
<th>$F_x [\text{N}]$</th>
<th>$F_y [\text{N}]$</th>
<th>$F_z [\text{N}]$</th>
<th>$M_x [\text{Nm}]$</th>
<th>$M_z [\text{Nm}]$</th>
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<td>50657</td>
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<td>$\pm 130$</td>
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<td>42257</td>
<td>-1343</td>
<td>-9743</td>
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</table>

Table 3.1: Loads on LOX on cone in load case “allumage, décollage, vent et rafale”

3. “extinction Epc”
4. “panne”
5. all other cases, including EAP extinction and separation (see table 3.2). Any combination of these numbers can occur.

<table>
<thead>
<tr>
<th>$F_x [\text{N}]$</th>
<th>$F_y [\text{N}]$</th>
<th>$F_z [\text{N}]$</th>
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<tr>
<td>-13917</td>
<td>-5543</td>
<td></td>
<td></td>
<td></td>
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Table 3.2: Loads on LOX on cone in unnamed load cases

Only the second and the fifth cases are required in combination with the accompanying cases.

SSHEL loads: it is considered that the SSHEL frame introduces more stiffness than the SSHEL equipment needs. It is a conservative approach to eliminate both the SSHEL frame and SSHEL loads.

LBS disconnection loads: the LBS assembly is subjected to loading from connection lines that are ruptured at take-off. Rupture occurs in two successive steps (see table 3.3).

One additional aspect should be mentioned. Next to mechanical loads provided by engine thrust and actuator loads, thermal loads need close consideration. Overall temperature in the structure during flight rises to a maximum value of 128°C near access hatches (ref. [7]). Material properties decrease at elevated temperature. Material properties should be used corresponding to the temperature at the particular instant of time.
ENGINE SUPPORT — ANALYSIS OBJECTIVES

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<th>( \phi ) 90</th>
<th>( \phi ) 30</th>
<th>other</th>
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<td>ECH, TPCO</td>
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<td></td>
<td>TPCH, ECO</td>
<td>PCE's</td>
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<tr>
<td>( F_{\text{dis}} )</td>
<td>24900 N</td>
<td>15970 N</td>
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<tr>
<td>( F_{\text{dyn}} )</td>
<td>( \pm )3180 N</td>
<td>( \pm )1310 N</td>
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<td>( T_{\text{dyn}} )</td>
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<td>( M_t )</td>
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<td>100 Nm</td>
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Table 3.3: LBS disconnection loads

when the load combination occurs. Maximum temperature is assumed to be 130°C (ref. [7]).

Looking at chronology of events, four major load cases are identified (ref. [4]):

- DEROAH at time 3.0s
- VROOAH at time 75.5s
- EPSYAH at time 107.0s
- EPDIATI at time 118.5s

Magnitudes of relevant load components are summarised in table 3.4.

<table>
<thead>
<tr>
<th>load case name</th>
<th>time</th>
<th>motor loads ( F_x ), ( F_y ), ( F_z ) [kN]</th>
<th>Lox on cone case no.</th>
<th>LBS loads</th>
<th>temperature ( ^\circ )C</th>
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<td>893.9, 12.6</td>
<td>2</td>
<td>yes</td>
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<tr>
<td>VROOAH</td>
<td>75.5</td>
<td>992.1, 178.2</td>
<td>2</td>
<td>no</td>
<td>130</td>
</tr>
<tr>
<td>EPSYAH</td>
<td>107.0</td>
<td>1167.1, 24.5</td>
<td>5</td>
<td>no</td>
<td>130</td>
</tr>
<tr>
<td>EPDIATI</td>
<td>118.5</td>
<td>1164.5, -22.6</td>
<td>5</td>
<td>no</td>
<td>130</td>
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Table 3.4: Loads at successive flight events

3.3 Objectives of the analysis

3.3.1 The notion of the collapse load

The response of a structure to loads that are acting on it, is nonlinear in general. The particular nonlinearity that is characteristic for the engine support is of a geometrical
and material nature. A consequence of this situation is that only the first part of the response history can be approximated by the linear solution of the governing equations.

There are two types of nonlinear responses that can be expected in general. One is a softening response and the other one is a hardening response (see figure 3.7). For

![Load-displacement curve](image)

**Figure 3.7**: Load–displacement curve in linear vs. nonlinear analysis: softening and hardening response

loads that are predominantly compressive as in the case considered here, one deals with the softening type of response. In this case the load versus deformation plot contains a maximum for the load at a so-called limit point.

The limit point signifies the point of instability. It is the point at which collapse of the structure occurs. An attempt to raise the load above the limit load will result in a dynamical departure from the last static equilibrium state. In that case the structure will collapse to destruction.

### 3.3.2 Buckling and bifurcation

A continuous and smooth response of a structure under load as depicted in figure 3.7 is the general case of the behavior of a structure such as the engine support. But nonlinear behavior can sometimes incorporate a bifurcation phenomenon. In such a case the initial load–deformation response is crossed by a secondary path of solutions. The behavior of the structure that is loaded at and beyond such a point is called buckling. The buckling process can be stable or unstable. In the latter case, the result of the buckling process is again catastrophic and the bifurcation point will then represent a first approximation of the load carrying capacity of the structure.
In the aerospace industry buckling problems arise because there is an ever lasting strife for weight saving. The process of weight optimization of a structure that carries compressive loads has the tendency to produce certain regularities in the design, such as symmetry, which make the structure prone to a behaviour dominated by bifurcation. For the engine support discussed in this report weight saving is also a primary issue, but, due to secondary design constraints any form of symmetry is absent. Buckling in the strict sense of its definition is therefore not an issue here.

A note of caution should be inserted here with regard to the use of the word buckling. Although buckling is a phenomenon that is associated with a bifurcation point in the equilibrium diagram of a given structure, the term buckling is also used for a large family of phenomena that are not strictly connected with bifurcation problems. This is particularly true for problems that differ only slightly from a true bifurcation problem and can be transformed to a bifurcation problem by (small) changes in the definition of the boundary conditions and geometry of the structure. Consequently, in the engineering practice the term “buckling” is used in a much wider context and it is in this context that it will be used here. (See, for instance, section 3.3.4).

3.3.3 Multi-parametric loading

In order to assess the load carrying capacity of the engine support, it is necessary to determine the limit load in the sense discussed above. At this point a difficulty arises. The loading on the engine support that must be considered here varies in time, not only with respect to its intensity, but also with respect to its form and type. This means that we deal with a multi parametric loading system and in that case the determination of the load carrying capacity is not simply the determination of a response curve as it is depicted in figure 3.7. For a multi-parametric loading system it is necessary, at least in principle, to consider all possible load combinations and to select from all of these combinations the case that yields the lowest limit load. In practice, this requirement is often too stringent as it would lead to an enormous effort in computation. In this report, the determination of the worst loading case is based on a pre-selection of a set of loading cases. This simplifies the task of determining the “worst” load case tremendously. The pre-selection of the loading cases in this report is based on engineering judgement and it is discussed in section 3.4 below.

3.3.4 Objective of the analysis

The stiffener/skin combinations that are used in the build-up of the cone are designed on the basis of “local buckling” strength criteria (see also the remark on the significance of the term “buckling” above). The sizing of the geometry of skin and stiffeners are carried out on the basis of the philosophy that local buckling should not take place after
a load level (in the worst case) of 1.2 times the design value is reached. The practical implication of this philosophy for the actual design is that out of plane deformations are allowed to occur at any stage of the loading process. These deformation patterns are characterized by wavelengths of the order of magnitude of the pitch between the stringers and their amplitudes are very small for load levels below the design load. Their growth will become significant only after the 1.2 load level is reached or exceeded. When the 1.2 level is exceeded, the structure will not collapse but simply become more flexible. It will then have lost stiffness at some rate but it will not collapse, at least not for some (finite) increase of the load beyond the 1.2 value.

With the finite element model discussed in this report, the local deformation effects can only be described in a very coarse manner due to limitations with respect to the extent the mesh grading can be carried out. In other words, local effects with a wave length of one half of the stiffener pitch are poorly represented in the models that were used. (See also section 5.3).

It should be emphasized, however, that the analysis reported here is focused on the behaviour of the cone with respect to deformations that are not local but global. In fact the analysis is aimed at showing that the point of failure of the structure on the basis of global deformations is sufficiently far away from the point at which local buckling deformations occur so that interaction between global and local effects can be ruled out. In other words, the analysis is aimed at showing that the global collapse load is sufficiently far above the local buckling load so that the 1.2 safety limit determined by the local buckling criteria can be accepted with confidence.

It follows from this observation that the weakness of the present finite element models — in the representation of deformations of very short wave length — is not a factor of concern, as long as the collapse point of the global investigation turns out to be far away from the 1.2 limit that is determined by the local effects. As it will become clear in the sequel, this condition is satisfied in all the cases that are considered.

The main point of this section can now be summarised as follows. The objective of the present investigation is to find a lower bound for the expected collapse load of the structure with respect to the global behaviour of the shell which should prove that this lower bound is sufficiently in excess of the local buckling limit set by the 1.2 “local buckling” boundary.

3.4 Selection of the worst load cases

Next to the baseline load case of maximum engine thrust, other load cases have to be considered. This section lists load cases that were considered to be potentially critical in nonlinear behaviour. This list is obviously shorter than the complete load case list, since only those load cases were retained that have an effect on the overall behaviour of
the engine frame. Loads that have only local effects are not considered. As in all of this study, any assumptions that are necessary are conservative. For some load cases, the effect they have on collapse and buckling is not obvious. A separate linear analysis shows which deformations occur. Table 3.5 summarises all load cases that were identified. It indicates which load cases will be considered in subsequent analysis. Load cases that

<table>
<thead>
<tr>
<th>load case</th>
<th>will be considered</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine thrust only</td>
<td>yes</td>
<td>EPSYAH</td>
</tr>
<tr>
<td>engine thrust + transverse y</td>
<td>no</td>
<td>VROOAH</td>
</tr>
<tr>
<td>engine thrust + transverse z</td>
<td>yes</td>
<td>EPSYAHVAO</td>
</tr>
<tr>
<td>engine thrust + LOX-line load</td>
<td>linear analysis</td>
<td>DEROAH</td>
</tr>
<tr>
<td>engine thrust + LBS loads</td>
<td>linear analysis</td>
<td></td>
</tr>
<tr>
<td>engine thrust + booster bar loads</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>engine thrust + temperature gradient</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>engine thrust at 130°</td>
<td>yes</td>
<td>EPSYAH130</td>
</tr>
<tr>
<td>engine thrust + transverse z at 130°</td>
<td>yes</td>
<td>VROOAH130</td>
</tr>
</tbody>
</table>

Table 3.5: List of load cases that are considered in nonlinear analysis

involve transverse loads on the meridian of the cone panels need closer consideration in linear analysis. A criterion is defined according to which load case results will be interpreted. It is felt that buckling and collapse loads of the structure decrease with transverse displacement of the cone panels. The decision as to which load cases will be considered in nonlinear analysis is based on maximum transverse displacement of cone panels: either LOX-line loads or LBS loads will further be studied as separate load case in nonlinear analysis.

Some other particular effects need closer consideration:

- initial deformation due to thermal gradient
- booster bar loads
- shape imperfections of the cone panels

The effect they have on collapse load will be clear only after nonlinear analysis of the primary and secondary mechanical load cases is completed.
Chapter 4

Availability of computational tools

This chapter first explains why the MSC/NASTRAN software code is used. It then describes the computer environment that is available at Faculty of Aerospace Engineering of the Technical University of Delft.

4.1 MSC/NASTRAN for nonlinear analysis

Several software codes are available for finite element analysis. This study explicitly requires nonlinear capabilities. Most modern finite element codes now provide nonlinear features. Many software codes are available at TUDelft: STAGS, B2000, ABACUS, MSC/NASTRAN, …

4.1.1 Selection of MSC/NASTRAN

At the time this study was initiated, the finite element models that were available at Fokker Space & Systems BV were considered unsuited for the proposed study. A new model was required. The preprocessing phase for an entirely new model with a fairly dense mesh and a lot of detail would require a long time to develop the model. None of the software packages mentioned above have a reliable and powerful preprocessor, except MSC/NASTRAN. It was decided to develop the model with MSC/XL, which has a direct interface with MSC/NASTRAN. At the time the study was initiated, MSC/XL version 2 was running on SUN workstations. After a few weeks, version 3 was available. All pre- and postprocessing for this study is done with MSC/XL version 3.

Initially, MSC/NASTRAN version 66B was running on the CONVEX. By the end of November 1991, version 67 became available. All analysis runs in this study are executed with MSC/NASTRAN version 67, except some preliminary analyses reported on in section 6.1, which are run in version 66B.
The nonlinear part of the code, which is used in this report is relatively new and is still under development (ref. [11]).

For the modelling of the engine support, it was necessary to use shell elements because the structure is basically a ring and stringer stiffened shell. The MSC/NASTRAN code possesses only one shell element that is suitable for nonlinear analysis. This is a quadrilateral four node element with a long standing history.

4.1.2 Implementation of the nonlinear solution procedure

MSC/NASTRAN provides two solution sequences for nonlinear static analysis:

- SOL 66 is an "unstructured" solution sequence
- SOL 106 is an "structured" solution sequence

Both sequences use the same options. Solution sequence SOL 66 is used. This sequence provides an incremental procedure and a path-following procedure. Path following procedures are not used in this study. The nonlinear equations are solved by continuation methods, also known as incremental–iterative methods or path following methods. These methods are designed to compute the load–deformation paths from the governing (discretised) equations. They produce, among others, curves of the type that are depicted in figure 3.7. In the latest version of the code (version 67), there are 4 variants of such a path following solution procedure available. It turned out, however, that only the "quasi–Newton" method could be used with success. The reason for this is discussed in section 4.3.

Next to the continuation procedures, there are also possibilities to compute the eigenmodes and eigenvalues of pure buckling problems in the case that the pre-buckling state is linear or nonlinear. These procedures are sometimes useful for preliminary investigations.

In the incremental method, the final load is subdivided in a number of subcases. Each subcase has a particular maximum load, and a number of increments before the maximum is reached. For each increment, convergence has to be reached before the next increment is initiated. Unless convergence is obtained after a number of iterations that is less than the parameter MAXITER, the analysis stops. The nonlinear properties of the model are defined on some specific MSC/NASTRAN bulk data entries. These parameters are discussed below.

In this study nonlinear behaviour is activated for every element. This is accomplished by putting all active degrees of freedom in the "analysis set" of the model. In SOL 66 of MSC/NASTRAN geometric nonlinearities are active by setting a parameter LGDISP:

PARAM LGDISP 1
Plate elements CQUAD4 and CTRIA3 do not provide stiffness for the rotational degree of freedom that is perpendicular to the tangent plane in a node of the elements. Degrees of freedom that do not possess stiffness cause the stiffness matrix to be singular unless they are eliminated. In linear analysis degrees of freedom that have no stiffness attached to them are eliminated automatically. In nonlinear analysis they are not. Singularities are suppressed by assigning an artificial default value to the stiffness of the corresponding degree of freedom. This value is expressed by the parameter K6ROT, that must be specified by the user. MSC/NASTRAN documentation does not provide much information on the actual value that should be assigned to this parameter. A value of $10^4$ is recommended by MSC Los Angeles for all present models (ref. 12):

PARAM K6ROT 1+4

Only the incremental procedure is used. Following parameter settings are selected:

<table>
<thead>
<tr>
<th>NLPARM</th>
<th>NINC</th>
<th>AUTO</th>
<th>PW</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1-3</td>
<td>1-7</td>
<td>30</td>
</tr>
<tr>
<td>1-3</td>
<td>1-3</td>
<td>-3</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

Card syntax for the NLPARM entry and comments for each data field are explained in section D.1. The third parameter NINC varies for each load case: values between 5 and 10 per subcase are used for different models. When large incremental rotations occur (RTOLB exceeds 20°), the bisection method is activated. The algorithm automatically divides the imposed increment by a factor of 2. In this way, load increments that are too large to handle in one step, are split in two consecutive load increments. This feature of the load incrementation procedure is activated throughout subsequent analysis runs, when loads approaches its collapse value.

Magnitude of load is controlled by imposing vertical displacement at the lower end of the structure. In models QU5 and BC2, the cross-cone interface displacement is imposed. In model BCC, the centre cardan displacement is imposed. Imposed displacement is preferred here rather than imposed load, because load-displacement curve is flat in the area close to collapse load.

4.2 The computer environment

The Faculty of Aerospace Engineering uses two computer platforms for technical work:

- network of SUN workstations (SUN 4/40 IPC, SUN 4/20 SLC) in a UNIX environment
- a CONVEX C240 mainframe (4 processors) in a UNIX environment
The former platform is used for pre- and postprocessing interactive work, whereas the latter is used as a batch machine for large computational jobs. Data transfer between both platforms is done with UNIX’ ftp (File Transfer Protocol). In this study, input files (MSC/NASTRAN - MSC/XL bulk data decks) are ASCII files, output files (MSC/NASTRAN - Msc/XL results database files .xdb) are binary. Files of both types are transferred directly.

4.3 Basic restrictions

Some problems have obstructed smooth progress of the study. Two types of problems have occurred:

- problems with computer capacity
- problems with computational MSC/NASTRAN algorithms

4.3.1 Computer capacity limitations

Despite its power and speed, the computer environment poses some limitations. 500 Mb of disk space is permanently available. This space is used for storing input, output and permanent database files. About 500 to 600 additional Mb is available on a temporary pool disk. It is available to all users on the CONVEX. This space is used for storing temporary work files.

Modern software codes are sufficiently powerful to handle models with many thousands of degrees of freedom. Analyses of that kind require huge amounts of disk space, both for the temporary and for the permanent storage areas:

permanent disk space: Since an incremental procedure generates stiffness matrices and deformation patterns for every single load step, database requirements are stringent. Solutions at intermediate load steps need to be stored on the database. In case the incremental procedure fails at a particular load step, and the previous load step is not saved on the database, restarts are not possible on that load level. Both the number of intermediate datablocks and their size need to be limited in order to allow the restart option to remain active. In this study, a restricted number of intermediate solutions are saved on the database (option NO on field 9 of NLPARM card).

temporary disk space: Scratch files are used to temporarily store datablocks which can not be stored in core memory. Scratch storage space is required primarily in the decomposition phase of the stiffness matrix. High numbers of degrees of
freedom require large amounts of disk space. It is felt that for this study the number of degrees of freedom should be limited to about 50,000. This model size corresponds to a required scratch space of 360 Mb.

The lack of symmetry in the geometry of the shell demands a discretisation that involves the complete 360° of the conical shell structure. If one adds to this demand that the blade stiffeners should be represented accurately, the required mesh would lead to a number of computational degrees of freedom of about 100,000. As one deals with nonlinear computations, the volume of data that need to be stored during the computations is at least an order of magnitude larger than that which belongs to a linear solution. This meant that with the available back-up memory of the Convex, a model of the size of 100,000 degrees of freedom could not be dealt with. Consequently, the memory restriction limited the size of the model that could be analyzed and it therefore dictated the use of a simplified model whereby symmetry around one or more planes of the cone were invoked (see section 5.1).

In the present computer configuration, the maximum number of degrees of freedom that can be handled in Msc/Nastran's nonlinear solution sequence SOL 66 is limited to 50,000. Processing times for such a model in the load cases presented in table 3.5 are typically 15 to 20 hours.

4.3.2 Msc/Nastran code limitations

As was mentioned in section 4.1, the continuation procedures are designed to compute the load-deformation relationship that is defined by the governing equations of equilibrium. It is possible to differentiate between two types of procedures of this kind. One type makes use of a form of Newton's method, while the other makes use of a form of the conjugate gradient method. This implies that the first approach relies on the use of derivatives of the equilibrium functions, while the other does not.

For the collapse analysis conducted here the first type of procedure is more suited. This follows because the determination of the limit point(s) of the solution curves can, in principle, be carried out without difficulties with the first method and this cannot be said about the second method. Moreover, experience with the use of these two different approaches that has been accumulated so far indicates that the first type of approach is more robust and in essence more efficient than the second approach.

Unfortunately, the procedures of the first kind that are available in Msc/Nastran turned out to be defective. This is due to an inconsistent derivation of the stiffness matrix pertaining to the nonlinear case. As a consequence, the results presented here could only be obtained by the second type of procedure. It explains why there are such numerous solution points along the curves that are shown.

The computations with this procedure were very time consuming which is manifested
by a very sluggish behaviour along the solution path. Bifurcation analyses on the basis of the current nonlinear state are not carried out due to limited available disk space.
Chapter 5

Modelling considerations

This chapter explains which considerations lead to the development of the present models.

5.1 General approach

The complexity of the structure is such that a particular model is required to accurately describe the nonlinear behaviour of the structure. A special approach is adopted.

5.1.1 The ideal model

Ideally, the best possible opportunity to study the behaviour of the engine support is furnished by a model in which a large extent of detail is presented. This means for example that one uses shell elements for every piece of material that presents itself as a shell in the structure and that one uses a meshing which is sufficiently dense to capture deformation patterns characterized by short waves. It also means that whenever in doubt, stiffeners are not represented by beams, but also by plate or shell elements. If it is possible to use a discretization in the above sense which includes the “complete” geometry of the engine support one can speak of an “ideal” model. It would then be possible to study the collapse behaviour under conditions that approximate reality accurately.

The feasibility of producing such a model exists. It would, however, lead to a discretisation that amounts to about 100,000 computational degrees of freedom and this volume turned out to be too large for the capacity of the computer environment in which the computations were carried out. The ideal or preferred model is therefore a possible object of study in the future as soon as it becomes feasible to meet the specific memory requirements that are connected with this model.
5.1.2 Regularity conditions

The restriction for not using the "ideal" model was in the first place the lack of back-up memory and in the second place the lack of speed of the central processor (CONVEX C240). To reduce the dimension of the computational space, the model had to be simplified in one way or another. The way the simplification were introduced here was by means of enforcing artificial regularity in the structure. By artificial regularity is meant that the actual structure is replaced by another structure which is composed of a number of identical parts of the actual structure. To be safe in this process, the "replacement" is constructed from that part of the original structure that is considered to be the weakest of the total assembly. For example, a model with one degree of regularity can be constructed in this manner by cutting the engine support in two sectors of 180° degrees. By taking that half which is considered to be the weakest, one can construct a structure with one symmetry plane. If the loading on the actual structure is also made symmetric in a manner which is consistent with the previous construction, the deformations of the resulting model will also be symmetric. This means then that it is possible to consider only one half of the structure as model. The number of computational degrees of freedom is reduced with a factor of about one half.

A further reduction is possible when the actual structure is replaced by a replacement structure with a degree of regularity of four, which corresponds to the use of only one quarter the actual structure and so on. In the present investigation use was made of two types of these models and these were 90° degree and 180° degree models.

The reduction of the computational model from the "ideal" to the "replacement" is carried out not only by a judicial choice of the weakest part of the actual structure but also by enforcing appropriate boundary conditions along the edges that are cut by the symmetry planes. These boundary conditions can be called symmetry or regularity conditions. The latter term is derived from the observation that the conditions should comply with the regularity of the expected solutions.

5.1.3 Simplifications

Apart from the simplification that are discussed above, several other simplification were introduced that should be mentioned. First of all, the connection of the engine support to the cylindrical shell, was modelled in a way that should be conservative. The attachment ring at this place is forced to stay on a plane perpendicular to the axis of the cone but is further unrestrained.

At the other end various conditions for the introduction of the loading were introduced depending on the model that was used. For the largest and most refined model (180° degrees) a special finite element construction was devised to simulate the effect load introduction through the engine support.
5.2 Constraints for the modelling of stiffeners

A number of requirements are defined in order to describe the buckling behaviour of the structure as accurately as possible:

- all degrees of freedom that are present in the structure and that may possibly cause buckling phenomena to occur must also be present in the finite element model. Two important examples illustrate this principle:
  - the stiffening effect obtained with two or more unflanged stiffeners should not be represented by a single stiffening element. Every single stiffener must be modelled.
  - elements representing the unflanged stiffeners should have degrees of freedom needed to describe local buckling phenomena. Bar or beam elements are not suited for this purpose. Rather plate elements must be used throughout the entire model. This element has bending stiffness in both element axes. It is capable of describing bending deformation of the stiffener about the longitudinal axis of the stiffener. Buckling modes initiated by this type of local buckling can be recovered with the model. The shape of a bar or beam cross section can not be deformed (fig. 5.1). Beam elements need to be connected with offsets. Plate elements have nodes at the element corners, no offsets are necessary.

- Panels and stiffeners are milled from a uniform plate with constant thickness of 50 mm, the radius at the root of the stiffener is 3.2 mm (fig. 5.2, scale 1/1). The material at the stiffeners' roots is omitted in a conservative approach.

- geometry of a plate element should be as simple as possible:
  - the taper property of the element should be reasonable

![Diagram](image.png)
Figure 5.2: Conservative modelling of unflanged stiffener section

- the aspect ratio of the element should be close to 1
- the element should not be warped strongly.
- the element should not be skew

Quadrilateral elements should be as square as possible. MSC/NASTRAN issues a warning message for every element that does not have the appropriate geometry. For this reason the mesh is prepared not to give any warning message.

5.3 Modelling rules and conventions

Constructing a finite element model involves the definition of some rules the modeller should use. Some rules evolve as a consequence of nonlinear modelling requirements, some rules can be imposed freely.

5.3.1 The cross assembly

The cross assembly transfers load to the cone assembly. Load transfer at the bottom of the cone panels and boundary conditions at the cone panels’ lower edges can only be described conveniently by an appropriate modelling of the interface between both assemblies. Any aspect of the cross assembly that has an effect on the load transfers at the lower cylinder interface is included in the model. The cross assembly is modelled in a somewhat hybrid way:

- the cross webs are modelled with very large elements that do not accurately represent the structure's geometry; their global stiffness matches the actual design values, though
the lower cylinder is modelled with small elements which closely represent the structure's design, circular stiffeners are included in the model and side webs transfer loads to the cylinder

Such a modelling strategy allows an accurate description of load transfer with a minimum number of degrees of freedom.

5.3.2 The cone assembly

Components of the cone assembly are expected to have a crucial effect on the nonlinear behaviour of the entire structure. The design features mentioned in chapter 3 are included in the model, if they are considered to be relevant.

panel dimensions: All panels have the exact dimensions, including thickness. Offsets of neutral planes are included in the model.

panel offsets: Apart of the fact that panels are curved, their outer faces are perfectly flat, i.e. variation in panels' thicknesses are visible only from the interior of the cone. Panels' neutral planes are shifted a small amount at connections between different panel's thicknesses. Resulting offsets cause eccentric load transfer and thus, bending moments. Cone panels are connected to each other with neutral planes that are shifted (see fig. 3.2). Offsets need to be incorporated in the model. However, nonlinear solution procedures do not allow offsets in the model because displacements are computed in a linear way. This approximation is false when large rotations occur. One way to work around offsets is the use of very short rigid elements. Rigid elements are not allowed in nonlinear analysis for the same reason offsets cause errors. This phenomenon is avoided by the use of very short beams with high, yet finite stiffness. This workaround involves double nodes very close to each other.

Shifting panel neutral planes are modelled in a particular fashion. All neutral planes are parallel. They all have the same angle at their apexes (fig. 5.3):

$$\theta = 36.49^\circ$$

Each neutral plane describes its own conical surface. All apexes of neutral planes are located on the longitudinal axis of the launcher. The vertical coordinate $z$ of the apex with respect to the apex of the theoretical cone is determined by the thickness of the cone panel $t$ (fig. 5.3):

$$z = \frac{7.5 - \frac{t}{2}}{\sin 36.49^\circ}$$

For each neutral plane a specific spherical coordinate system is defined. Nodes located in a particular neutral plane are defined in the corresponding coordinate
Figure 5.3: Modelling of cone panel offsets
system. The identification number of the coordinate system is equal to 10 times the panel thickness at that node. Node coordinates are presented with three numbers $R$, $\phi$, $\theta$, which are easily interpreted. $R$ is the radius measured along a meridian, as it is indicated on the drawings. $\phi$ is the angle of the cone, which is constant $36.49^\circ$. $\theta$ is the circumferential angle. $\theta = 0^\circ$ at the global Y-axis. There are some exceptions to the rule: nodes located at the interface between two panels with different thicknesses are positioned at the neutral plane of the thicker of both panels.

**cone – cross connection**: connection between cone and cross is designed with a double row of bolts (fig. 5.4). The overlapping connection does not generate any bending moments since neutral planes of both panels’ ends coincide. The model features an in-plane connection.

**box – cone interface**: a major point of concern is the connection between the box assembly and the cone assembly (fig. 5.5). It is a doubly overlapping joint with three rows of bolts. Since this connection is considered to be a critical point, it is modelled with a high number of nodes in a very dense mesh. Nodes have the actual coordinates and eccentric locations are accurately described. Bolts are stiff with respect to the structural panels they connect, because they are very short. Rigid elements can not be used though, since displacements are not computed correctly when large rotations occur. For that reason bolts are given a finite stiffness, corresponding to a diameter of 15 mm:

\[
A = 1.767 \times 10^{-4} m^2 \quad I = 2.485 \times 10^{-9} m^4
\]

Bolts are modelled as CBEAM elements, which are appropriate for large rotations.

**holes in panels**: Holes are included in the model at their exact locations, with exact dimensions. Only radii in the corners of holes are omitted, again this approach is conservative. Panel and stiffener thicknesses are increased at the edges of holes, with values of the actual design.
lap joint connections: usually, individual panels have the same thickness as the surrounding panels; the modelled panel thickness is equal to the smaller of both individual values, bolts are omitted and elements are connected in a continuous way.

equipment loads and brackets: cone panels are stiffened locally to smoothly introduce equipment loads; since VAO loads (Vanne d'Alimentation Oxygène) will be considered further, the LOX beams are incorporated in the model.

ring frame stiffeners: three intermediate ring frames are modelled. Wall thickness of the ring frames is constant 3 mm. Ring frame meridional cross-sections are modelled with two elements for the ring frame floor and two elements for the ring frame wall (fig. 5.6). In this way, deformation of both ring frame webs can be represented. If ring frames would have a tendency to buckle, this mesh is capable of describing bending deformation in both parts.

With the modelling options listed above, all structural aspects that are expected to be important to the overall behaviour of the cone assembly are included in the model.

5.3.3 The box assembly

Components of the box assembly may possibly affect the nonlinear behaviour of the entire structure. Some design features mentioned in chapter 3 are included in the model. They are all modelled in a very conservative way:
the box floor: The floor is a stiffened plate with variable thickness and variable stiffener dimensions. Unflanged stiffeners are represented by plate elements without offsets. In the model, floor component dimensions are constant along the perimeter of the floor. Minimum section properties are assumed for the entire perimeter (fig. 5.7).

the box cylinder: The panels are modelled with plate elements stiffened with beam elements with no offsets: two large flanges are on top of the cylinder panels, they are modelled with beam elements (fig. 5.8). In the model, cylinder plate dimensions are constant along the perimeter of the wall. Minimum section properties are assumed for the entire perimeter.

conical panels: Uniform properties are assumed along the perimeter. Modelling conventions are the same as for the panels of the cone assembly.

box radial webs: 26 webs are included in the 180° model

This model incorporates all features that are expected to be relevant for the nonlinear behaviour of the structure. Other aspects are modelled in such a way as to accurately represent the structural behaviour. The model is dense in regions where it should be.
5.4 Material properties

In the present analyses the structure is loaded to its maximum capacity. Loads may substantially exceed the limit design load. Geometrically large displacements change both the overall stiffness of the structure and the load pattern the structure is subjected to. Next to that, material behaviour probably does not stay in the elastic domain. The nonlinear behaviour of the material is incorporated in the analysis. Both linear and nonlinear properties of the material are extracted from the material’s MIL handbook (ref. 22). Following data are provided for Al7075-T7351. Most of the structure’s components are machined from plate material with an original thickness of 50 mm. Therefore material category 1.5–2.0 in is selected. In each category class A and class B values are provided. Class A corresponds to 99% of the population of values expected to equal or exceed the mechanical property allowable, with a confidence of 95%. Class B corresponds to 90% of the population of values expected to equal or exceed the mechanical property allowable, with a confidence of 95%. The material possesses properties which depend on the orientation of grains. An isotropic model describes the material behaviour, rather than an anisotropic one which accurately represents each individual direction inside a material’s specimen (L, LT, ST). If any other assumptions are necessary, it is attempted to select them in a conservative way with respect to the stiffness of the structure.

Elastic properties are derived from Table 3.7.4.0(b3) (MIL–HDBK):

**modulus of elasticity**: although the major portion of the structure is loaded in compression, the value corresponding to tensile stresses is used. Bending moments generate tensile stresses in buckling sensitive areas.

\[ E_{\text{tension}} = 10300 \text{ksi} \quad E_{\text{compression}} = 10600 \text{ksi} \]
The tensile value is 3% lower than the compressive value:

\[ E = E_{\text{tension}} = 71.02 \frac{GN}{m^2} \]

**Poisson's ratio**:

\[ \nu = 0.33 \]

Plastic properties are derived from Figure 3.7.4.2.6(e) (MIL-HDBK):

**yield stress**: compressive values are lower than tensile values, except for the transverse short orientation ST. Stresses in the transverse short material direction ST

<table>
<thead>
<tr>
<th></th>
<th>( F_{ty} ) [ksi]</th>
<th>( F_{cy} ) [ksi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>longitudinal L</td>
<td>55</td>
<td>53</td>
</tr>
<tr>
<td>transverse — long LT</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td>transverse — short ST</td>
<td>52</td>
<td>59</td>
</tr>
</tbody>
</table>

Table 5.1: Tensile and compressive yield stresses of Al7075-T7351 at room temperature

are not important. The value for longitudinal orientation L in compressive loading is selected:

\[ F_y = 365.4 \frac{MN}{m^2} \]

**strain hardening**: the curved part of the stress-strain curve is represented by a straight line,

\[ E_{\text{tangent}, L} = 194.6 \frac{MN}{m^2} \quad \quad E_{\text{tangent}, LT} = 430.9 \frac{MN}{m^2} \]

which is again a conservative assumption:

\[ E_{\text{tangent}} = 194.6 \frac{MN}{m^2} \]

The numerical representation of the material behaviour both in elastic and in plastic domain at room temperature is shown in fig. 5.9. These parameters are defined on Msc/NASTRAN MAT1 and MATS1 entries (see appendix C for an explanation of card syntax):

MAT1  10  71.02+9   0.33
MATS1  10  PLASTIC 194.6+6   365+6
Figure 5.9: Modelled material behaviour at room temperature

The launcher operates at different temperatures. It is considered to take off at room temperature. During flight temperature increases to a maximum of 130°C. Material properties change with temperature. At 130°C they are lower than at room temperature. Separate load cases are run with material properties at 130°C. Exact temperature dependencies are not provided in ref. 22 for Al7075-T7351. Properties are derived from tables and figures which are valid for Al7075-T6. Figures 3.7.4.1.1c,d, 3.7.4.1.2a, 3.7.4.1.4 and 3.7.4.1.5a (MIL-HDBK) provide information on the temperature effect on tensile ultimate stress $F_{tu}$, tensile yield stress $F_{ty}$, compressive yield stress $F_{cy}$, compressive and tensile elastic moduli $E_c$ and $E_t$, and elongation $\epsilon$ :

- compressive elastic modulus (92%) :
  \[ E_{c,130^\circ C} = 0.92 E_{c,room} = 67.2 \frac{GN}{m^2} \]

- tensile elastic modulus (92%) :
  \[ E_{t,130^\circ C} = 0.92 E_{t,room} = 65.3 \frac{GN}{m^2} \]

- tensile yield stress (84%) :
  \[ F_{ty,130^\circ C} = 0.84 F_{ty,room} = 318.4 \frac{MN}{m^2} \]
MODELLING CONSIDERATIONS

- Tensile ultimate stress (80%):
  \[ F_{tu,130^\circ C} = 0.8 E_{tu,room} = 364 \frac{MN}{m^2} \]

- Compressive yield stress (83%):
  \[ F_{cy,130^\circ C} = 0.83 E_{cy,room} = 303 \frac{MN}{m^2} \]

- Elongation (120\%):
  \[ \varepsilon_{130^\circ C} = \varepsilon_{room} = 7.2\% \]

The numerical representation of the material behaviour both in elastic and in plastic domain at 130\(^\circ\)C is shown in fig. 5.10. These parameters are defined on Msc/Nastran.

![Material behaviour graph](image)

**Figure 5.10: Modelled material behaviour at 130\(^\circ\)C**

**MAT1 and MATS1 entries** (see appendix C for an explanation of card syntax):

<table>
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<tr>
<th>MAT1</th>
<th>10</th>
<th>65.3+9</th>
<th>0.33</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATS1</td>
<td>10</td>
<td>PLASTIC</td>
<td>630+6</td>
</tr>
</tbody>
</table>

Different material properties require separate nonlinear analysis runs.
Chapter 6

Computations and basic results

In order to get a feeling for both the behaviour of the structure and for the particular features of nonlinear analysis with MSC/NASTRAN, some preliminary problems are defined with gradually increasing difficulty.

6.1 Preliminary analyses

Some problems are considered that are not directly related to the present study of the EPC-BME.

6.1.1 Sample problems

First the nonlinear capabilities of MSC/NASTRAN are verified for their validity. In a first step some problems are considered that can be compared with results from sources external to MSC/NASTRAN and its related documentation. Some problems are published in literature, some others are analysed with different software packages (STAGS, SOLVIA):

- section of a thin-walled cylinder with unflanged stiffeners, loaded in compression
- flat plate with stiffeners, loaded in compression
- snap-through of a spherical shell segment, that is loaded with a transverse force component

All results obtained with MSC/NASTRAN compare well with results from the other source.
6.1.2 Coarse grid model engine frame

Ref. [6] gives a description of a coarse grid model of the ARIANE 5 engine frame. This model has about 800 nodes. It is used at Fokker Space & Systems BV for general stiffness and internal load distribution analyses. Some modifications are needed to prepare the model for nonlinear analysis:

- bar elements CBAR, that can not be used for large displacement analysis, are replaced by more general beam elements CBEAM
- offsets are translated to a linearised formulation, so they can not be included in nonlinear analysis. Offsets are removed in this model.
- only the baseline load case is considered
- only linear elastic material properties are considered

Load is incremented gradually up to five times limit load. It turns out that with this model the structure behaves in an almost perfectly linear way. It is obvious however, that results obtained with this model can not be interpreted reliably in a nonlinear investigation of the structure, because:

- even before the model was modified it does not provide sufficient detail of the structure, although its stiffness is representative for the actual behaviour of the structure
- offsets are used throughout the entire structure, so removal of them is not a fair approximation of the structural behaviour

This analysis gives some insight in both the overall behaviour of the structure and nonlinear procedures of MSC/NASTRAN.

6.2 Results for the 90° model

It is expected that nonlinear behaviour primarily affects cone panels. At certain load levels, which still need to be determined, transverse displacement of cone panels will occur. The box structure possibly exhibits a nonlinear load-displacement relationship. For that reason two consecutive models are considered:

- the first model QU5 features only cone panels with unflanged stiffeners and ring frames, the model is simply supported at the cone - cross interface and at the box-cone interface, see section A.1 for details on model characteristics and boundary conditions
• the second model BC2 also includes the box assembly, the model is simply supported at the cone-cross interface and at the RIE interface, see section A.2 for details on model characteristics and boundary conditions.

For model QU5, load is incremented in nine subcases. Each subcase then has a number of load increments between 4 and 10. Load magnitude is controlled by imposing vertical displacement at the lower edge. Vertical displacement of the lower cylinder goes up to 35 mm. The reaction force that is needed to hold the model at the imposed displacement corresponds to the engine thrust applied at the lower cylinder. Material properties are linear in this run. Figure 6.1 displays the load–displacement curve.

![Load–displacement curve for model QU5](image)

Figure 6.1: Load–displacement curve for model QU5

Since this model represents only one quarter cone, vertical reaction force that is computed in nonlinear analysis has to be multiplied by a factor of 4 to obtain total motor load. The horizontal line indicates limit load in the baseline load case with an engine thrust of 1.167 MN. With this model, collapse load is:

$$4 \times 1.31\text{MN} = 5.24\text{MN}$$

Margin of safety is then:

$$MS = \frac{5.24}{1.167} - 1 = 3.49$$
It appears that the structure behaves in an almost perfectly linear way up to load levels of 3.5 to 4 times limit load. The deformation pattern that corresponds to the collapse load is shown in fig. 6.2. The access hatch area is most critical. The side with the widest strip between access hatch edge and unflanged stiffener is weakest.

### 6.3 Results for the 180° model

This model includes all components that are expected to possibly contribute to the nonlinear behaviour of the engine frame. Detailed model characteristics are given in section A.3. Modelling rules presented in sections 5.1 and 5.3 are applied. Boundary conditions are listed in section A.3. Rules that are used to select boundary conditions are commented in section 5.2.

This model is used to run all load cases that are identified to be possibly critical. These load cases are listed in section 3.4. Load case EPSYAH is the baseline load case. All other cases are compared to the baseline load case.

#### 6.3.1 Load case EPSYAH

Load is incremented in three subcases. Load magnitude is controlled by imposing vertical displacement at the centre cardan. Output is requested only at the last increment of a subcase, in order to keep database and output files of reasonable size. For the last subcase however, full output is requested. Load incrementation scheme is shown in table 6.1.

<table>
<thead>
<tr>
<th>subcase</th>
<th>increments</th>
<th>maximum displacement [mm]</th>
<th>intermediate output</th>
</tr>
</thead>
<tbody>
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<td>20</td>
<td>no</td>
</tr>
<tr>
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<td>30</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>40</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.1: Load incrementation scheme for load case EPSYAH

When incremental rotations are too large, the bisection method is activated and the load incrementation scheme is modified. Table 6.2 lists how the solution procedure evolves. The last column gives the number of iterations that are needed before convergence is achieved. Figure 6.3 displays the load–displacement curve.

Since this model represents half a cone, vertical reaction force that is computed in nonlinear analysis has to be multiplied by a factor of 2 to obtain total motor load. The horizontal line indicates limit load in the baseline load case with an engine thrust of
Figure 6.2: Collapse mode for model QU5, $MS = 3.49$
<table>
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<th>displacement [mm]</th>
<th>load [MN]</th>
<th>iterations #</th>
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<td>5</td>
<td></td>
<td>8</td>
</tr>
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<td>no</td>
<td>7.5</td>
<td></td>
<td>10</td>
</tr>
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<td></td>
<td>4</td>
<td>no</td>
<td>10</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>7</td>
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<td>no</td>
<td>17.5</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
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<td>no</td>
<td>20</td>
<td></td>
<td>7</td>
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<td>no</td>
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<td>1.778</td>
<td>6</td>
</tr>
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<td>23.75</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>no</td>
<td>25</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>no</td>
<td>26.25</td>
<td></td>
<td>9</td>
</tr>
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<td></td>
<td>14</td>
<td>no</td>
<td>27.5</td>
<td></td>
<td>13</td>
</tr>
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<td></td>
<td>15</td>
<td>no</td>
<td>28.75</td>
<td></td>
<td>18</td>
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<tr>
<td></td>
<td>16</td>
<td>no</td>
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<td>31.5</td>
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<td>yes</td>
<td>31.625</td>
<td>2.530</td>
<td></td>
<td>6</td>
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<td></td>
<td>yes</td>
<td>31.6875</td>
<td>2.530</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Table 6.2: Modified load incrementation scheme for load case Epsyah

1.167 MN. In this load case, collapse load is:

\[ 2 \times 2.530\text{MN} = 5.059\text{MN} \]

Margin of safety is then:

\[ MS = \frac{5.059}{1.167} - 1 = 3.335 \]

The deformation pattern that corresponds to the collapse load is shown in fig. 6.4. The access hatch area is most critical.

### 6.3.2 Load case Epsyah130

Load is incremented in three subcases. Load magnitude is controlled by imposing vertical displacement at the centre cardan. Output is requested only at the last increment of a subcase, in order to keep database and output files of reasonable size. For the last subcase however, full output is requested. Load incrementation scheme is shown in table 6.3.
Figure 6.3: Load–displacement curve for load case EPSYAH

Figure 6.4: Collapse mode for load case EPSYAH, $M_S = 3.335$
<table>
<thead>
<tr>
<th>subcase</th>
<th>increments</th>
<th>maximum displacement [mm]</th>
<th>intermediate output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>20</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>26</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>35</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.3: Load incrementation scheme for load case EPYAH130

When incremental rotations are too large, the bisection method is activated and the load incrementation scheme is modified. Table 6.4 lists how the solution procedure evolves. The last column gives the number of iterations that are needed before convergence is achieved. Figure 6.5 displays the load–displacement curve.

Since this model represents half a cone, vertical reaction force that is computed in nonlinear analysis has to be multiplied by a factor of 2 to obtain total motor load. The horizontal line indicates limit load in the baseline load case with an engine thrust of 1.167 MN. In this load case, collapse load is:

\[ 2 \times 2.149 \text{ MN} = 4.299 \text{ MN} \]

Margin of safety is then:

\[ MS = \frac{4.299}{1.167} - 1 = 2.684 \]

The deformation pattern that corresponds to the collapse load is shown in fig. 6.6. The access hatch area is most critical.

### 6.3.3 Load case VROOAH

Transverse load is applied at the centre cardan. According to technical specifications ref. [2] and the loads report ref. [4], this force is directed either along the global Y-axis, or along the global Z-axis. In load case EPDIATI at time 118.5 s transverse load in global Y-direction is applied. In other load cases, especially load case VROOAH at time 75.5 s, transverse load is directed along the global Z-axis. A symmetric model with a plane of symmetry along the bisection of global Y- and global Z- axes cannot be loaded with a load directed along either one of both global axes, without disturbing symmetry. It is decided therefore, to apply maximum transverse load, directed in any direction, along the plane of symmetry. In this way, symmetry of the model is not disturbed. This approach is conservative, because it applies loads in a direction that is more critical than the nominal direction.

Load is incremented in three subcases. Load magnitude is controlled by imposing vertical displacement at the centre cardan. Transverse load at the centre cardan however is controlled by magnitudes of force. Both vertical displacement and transverse force are increased simultaneously. They are independent however. Since the structure behaves in
Figure 6.5: Load–displacement curve for load case EPSYAH130

Figure 6.6: Collapse mode for load case EPSYAH130, $MS = 2.684$
### Table 6.4: Modified load incrementation scheme for load case EPSYAH130

<table>
<thead>
<tr>
<th>subcase #</th>
<th>load increment</th>
<th>bisection</th>
<th>displacement [mm]</th>
<th>load [MN]</th>
<th>iterations</th>
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<tbody>
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<td>1</td>
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</table>

A nonlinear way at elevated load levels, reaction force and transverse force do not always have a constant ratio. Output is requested only at the last increment of a subcase, in order to keep database and output files of reasonable size. For the last subcase however, full output is requested. Load incrementation scheme is shown in table 6.5. The fourth column is the load factor for the transverse load.

When incremental rotations are too large, the bisection method is activated and the load incrementation scheme is modified. Table 6.6 lists how the solution procedure evolves. The last column gives the number of iterations that are needed before convergence is achieved. Figure 6.7 displays the load–displacement curve.

Since this model represents half a cone, vertical reaction force that is computed in nonlinear analysis has to be multiplied by a factor of 2 to obtain total motor load. The horizontal line indicates limit load in the baseline load case with an engine thrust of 1.167 MN. In this load case, collapse load is:

\[ 2 \times 1.822\, MN = 3.645\, MN \]
Table 6.5: Load incrementation scheme for load case VROOAH

<table>
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<th>subcase</th>
<th>load increment</th>
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<th>displacement [mm]</th>
<th>load [MN]</th>
<th>transverse load factor</th>
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</tr>
</tbody>
</table>

Table 6.6: Modified load incrementation scheme for load case VROOAH

<table>
<thead>
<tr>
<th>subcase</th>
<th>load increment</th>
<th>bisection</th>
<th>displacement [mm]</th>
<th>load [MN]</th>
<th>transverse load factor</th>
<th>iterations #</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>9</td>
<td>no</td>
<td>16</td>
<td>2.4</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>no</td>
<td>17</td>
<td></td>
<td>2.55</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>no</td>
<td>18</td>
<td></td>
<td>2.7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>no</td>
<td>19</td>
<td></td>
<td>2.85</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>no</td>
<td>20</td>
<td>1.731</td>
<td>3</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>yes</td>
<td>21</td>
<td>1.781</td>
<td>3.15</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>21.5</td>
<td>1.803</td>
<td>3.225</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>22</td>
<td>1.822</td>
<td>3.3</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>22.125</td>
<td>1.818</td>
<td>3.31875</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>22.1875</td>
<td>1.813</td>
<td>3.328125</td>
<td>18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Margin of safety is then:

\[ MS = \frac{3.645}{1.167} - 1 = 2.123 \]

Transverse load and vertical load are not proportional to each other, so transverse load has a different margin of safety:

\[ MS = 3.3 - 1 = 2.3 \]

The deformation pattern that corresponds to the collapse load is shown in Fig. 6.8. The access hatch area is most critical.
Figure 6.7: Load–displacement curve for load case VROOAH

Figure 6.8: Collapse mode for load case VROOAH, MS = 2.123
6.3.4 Load case Epsyahvao

This load case deals with loads that are applied in a direction that is perpendicular to the individual cone panels. It requires some preliminary investigations to find out which load combinations are most critical to the structure when nonlinear analysis behaviour is considered.

Preliminary linear analysis

In this load case loads that are perpendicular to the cone are taken into account. It is not clear at the beginning however, which transverse load components have the most serious effect on the structure's nonlinear behaviour. The load case report ref. [4] identifies two major cases that involve loads directed perpendicular to the cone's meridian:

- load case Deroah at time 3.0 s includes loads applied at the lbs assembly; these loads are directed primarily along the longitudinal axis of the launcher; at this time, motor loads are not very high though

- transverse loads on the LOX on cone connection: this load can occur at several flight events

It is felt that the effect of secondary load components on the structure's nonlinear behaviour can be correlated to the transverse displacement of the panels. The panels have high stiffness in meridional direction, stiffness for loads in the perpendicular direction is much smaller. Loads of medium to low magnitude have non-negligible effect on transverse deformation. In case transverse displacements caused by secondary load components have the same sign as transverse displacements due to nonlinear effects, the combined effect will result in a decrease of collapse load. The effect of secondary loads is investigated in a separate linear analysis run. The model that is used in this run is the linear finite element model that was used at Fokker Space & Systems BV at the current stage of development. It is described in ref. [8]. Major structural properties have not changed much since that time, and detailed results of this model will not be used anyway. This model now only gives an idea on which load cases cause large displacements. Four groups of load cases are considered, corresponding to the major flight events. They all have the baseline load as a primary load component. Secondary load components are added according to the load case report ref. [4]. In this section, LOX on cone loads and LBS loads are considered as secondary load cases. Loads are defined in a specific coordinate system:

- engine loads are specified in the basic coordinate system $XYZ: F_X$ is the load component in the vertical direction, $F_Y$ is the transverse load component directed towards solid propellant boosters, $F_Z$ is the transverse load component directed towards LOX- and LH2- lines
- LOX on cone loads are specified in the cylindrical coordinate system \( r\theta z \) at the LOX on cone connection: \( F_r \) is the load component in radial direction, \( F_z \) is the load component in vertical direction

- LBS load components are defined in their own coordinate system which is either rectangular \( xyz \), or cylindrical \( r\theta z \):
  - rectangular ECH, TPSO
  - cylindrical EPSH, ERVH, EPSO, ERVO, ECO, PCE-H, PCE-O, PCP-H, PCP-O, TPCH

Maximum and minimum load combinations are investigated. Four groups are identified:

- group 10 load case DER0A0H time 3 s, plus secondary loads listed in table 6.7.
- group 20 load case VROOA0H time 75.5 s, plus secondary loads listed in table 6.8.
- group 30 load case EPSYA0H time 107 s, plus secondary loads listed in table 6.9.
- group 40 load case EPDIATI time 118.5 s, plus secondary loads listed in table 6.10.

For each load case, displacement in a direction perpendicular to the cone tangent plane is considered. Displacement \( u_\phi \) is positive in the positive \( +\phi \) direction of the spherical coordinate system. The positive \( +\phi \) direction points outward to the cone. The areas where minimum and maximum displacements are found are identified with spherical coordinates:

- \( R \) is the radius of the spherical coordinate system, \( R = 1.5m \) at the lower panels' edge (lower cylinder), \( R = 4m \) at the upper panels' edge (cone-box connection)

- \( \theta \) is the angle around the longitudinal axis of the launcher, \( \theta = 0^\circ \) at the global \( +Y \)-axis, the LOX- hole is located around \( \theta = 270^\circ \)

Table 6.11 gives minimum and maximum displacements for load cases in group 10. Table 6.12 gives minimum and maximum displacements for load cases in group 20. Table 6.13 gives minimum and maximum displacements for load cases in group 30. Table 6.14 gives minimum and maximum displacements for load cases in group 40.

Transverse displacements are largest in the LOX on cone load cases, in combination with engine load cases EPSYA0H and EPDIATI. In nonlinear analysis due to engine thrust the LOX- hole exhibits negative displacement, i.e. directed towards the inside of the cone assembly. Load cases 31 and 41 give maximum displacement (with negative sign). Loads on LOX on cone connection will be investigated further in nonlinear analysis:

\[
F_r = -F_Z = -46.46kN \quad F_Z = F_X = -1.597kN
\]

LBS loads will no longer be considered.
### Table 6.7: Load cases for preliminary linear analysis DEROAH 3.0 s

<table>
<thead>
<tr>
<th>load case</th>
<th>engine thrust</th>
<th>LOX on cone</th>
<th>LBS load components</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = -50.66 \text{kN}$</td>
<td>Epsh, Ervh, Ech,</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -2.77 \text{kN}$</td>
<td>Epso, Ervo, Tpco</td>
</tr>
<tr>
<td>12</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = -50.66 \text{kN}$</td>
<td>Eco, Pce-H, Pce-O</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -2.77 \text{kN}$</td>
<td>Tpch, Pcp-H, Pcp-O</td>
</tr>
<tr>
<td>13</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = 9.74 \text{kN}$</td>
<td>Epsh, Ervh, Ech,</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -2.77 \text{kN}$</td>
<td>Epso, Ervo, Tpco</td>
</tr>
<tr>
<td>14</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = 9.74 \text{kN}$</td>
<td>Eco, Pce-H, Pce-O</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -2.77 \text{kN}$</td>
<td>Tpch, Pcp-H, Pcp-O</td>
</tr>
<tr>
<td>15</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = -50.66 \text{kN}$</td>
<td>Epsh, Ervh, Ech,</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -15.09 \text{kN}$</td>
<td>Epso, Ervo, Tpco</td>
</tr>
<tr>
<td>16</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = -50.66 \text{kN}$</td>
<td>Eco, Pce-H, Pce-O</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -15.09 \text{kN}$</td>
<td>Tpch, Pcp-H, Pcp-O</td>
</tr>
<tr>
<td>17</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = 9.74 \text{kN}$</td>
<td>Epsh, Ervh, Ech,</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -15.09 \text{kN}$</td>
<td>Epso, Ervo, Tpco</td>
</tr>
<tr>
<td>18</td>
<td>$F_X = 893.9 \text{kN}$</td>
<td>$F_r = 9.74 \text{kN}$</td>
<td>Eco, Pce-H, Pce-O</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 12.55 \text{kN}$</td>
<td>$F_z = -15.09 \text{kN}$</td>
<td>Tpch, Pcp-H, Pcp-O</td>
</tr>
</tbody>
</table>

### Table 6.8: Load cases for preliminary linear analysis VROOAH 75.5 s

<table>
<thead>
<tr>
<th>load case</th>
<th>engine thrust</th>
<th>LOX on cone</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>$F_X = 992.1 \text{kN}$</td>
<td>$F_r = -50.66 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 178.2 \text{kN}$</td>
<td>$F_z = -2.77 \text{kN}$</td>
</tr>
<tr>
<td>23</td>
<td>$F_X = 992.1 \text{kN}$</td>
<td>$F_r = 9.74 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 178.2 \text{kN}$</td>
<td>$F_z = -2.77 \text{kN}$</td>
</tr>
<tr>
<td>25</td>
<td>$F_X = 992.1 \text{kN}$</td>
<td>$F_r = -50.66 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 178.2 \text{kN}$</td>
<td>$F_z = -15.09 \text{kN}$</td>
</tr>
<tr>
<td>27</td>
<td>$F_X = 992.1 \text{kN}$</td>
<td>$F_r = 9.74 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 178.2 \text{kN}$</td>
<td>$F_z = -15.09 \text{kN}$</td>
</tr>
</tbody>
</table>

### Table 6.9: Load cases for preliminary linear analysis EPSYAH 107 s

<table>
<thead>
<tr>
<th>load case</th>
<th>engine thrust</th>
<th>LOX on cone</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>$F_X = 1167.1 \text{kN}$</td>
<td>$F_r = -46.46 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 24.5 \text{kN}$</td>
<td>$F_z = -1.60 \text{kN}$</td>
</tr>
<tr>
<td>33</td>
<td>$F_X = 1167.1 \text{kN}$</td>
<td>$F_r = -5.54 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 24.5 \text{kN}$</td>
<td>$F_z = -1.60 \text{kN}$</td>
</tr>
<tr>
<td>35</td>
<td>$F_X = 1167.1 \text{kN}$</td>
<td>$F_r = -46.46 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 24.5 \text{kN}$</td>
<td>$F_z = -13.92 \text{kN}$</td>
</tr>
<tr>
<td>37</td>
<td>$F_X = 1167.1 \text{kN}$</td>
<td>$F_r = -5.54 \text{kN}$</td>
</tr>
<tr>
<td></td>
<td>$F_Z = 24.5 \text{kN}$</td>
<td>$F_z = -13.92 \text{kN}$</td>
</tr>
</tbody>
</table>
### COMPUTATIONS — BASIC RESULTS

<table>
<thead>
<tr>
<th>load case</th>
<th>engine thrust</th>
<th>LOX on cone</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>$F_X = 1164.5kN$</td>
<td>$F_r = -46.46kN$</td>
</tr>
<tr>
<td></td>
<td>$F_Y = -22.56kN$</td>
<td>$F_z = -1.60kN$</td>
</tr>
<tr>
<td>43</td>
<td>$F_X = 1164.5kN$</td>
<td>$F_r = -5.54kN$</td>
</tr>
<tr>
<td></td>
<td>$F_Y = -22.56kN$</td>
<td>$F_z = -1.60kN$</td>
</tr>
<tr>
<td>45</td>
<td>$F_X = 1164.5kN$</td>
<td>$F_r = -46.46kN$</td>
</tr>
<tr>
<td></td>
<td>$F_Y = -22.56kN$</td>
<td>$F_z = -13.92kN$</td>
</tr>
<tr>
<td>47</td>
<td>$F_X = 1164.5kN$</td>
<td>$F_r = -5.54kN$</td>
</tr>
<tr>
<td></td>
<td>$F_Y = -22.56kN$</td>
<td>$F_z = -13.92kN$</td>
</tr>
</tbody>
</table>

Table 6.10: Load cases for preliminary linear analysis EPIATI 118.5 s

<table>
<thead>
<tr>
<th>load case</th>
<th>$u_{\phi,max}$ [mm]</th>
<th>$u_{\phi,min}$ [mm]</th>
<th>area where it occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.3</td>
<td>-2.1</td>
<td>$R \approx 2.75m, \theta \approx 315^\circ$ meridional edges of LOX- hole</td>
</tr>
<tr>
<td>12</td>
<td>1.2</td>
<td>-2.0</td>
<td>$R \approx 2.75m, \theta \approx 315^\circ$ around LOX- hole</td>
</tr>
<tr>
<td>13</td>
<td>1.1</td>
<td>-0.8</td>
<td>large area around LOX- hole $	heta \approx 205^\circ$, $\theta \approx 320^\circ$</td>
</tr>
<tr>
<td>14</td>
<td>1.5</td>
<td>0.7</td>
<td>around LOX- hole entire LBS- quadrant</td>
</tr>
<tr>
<td>15</td>
<td>1.0</td>
<td>-1.4</td>
<td>$R \approx 2.75m, \theta \approx 315^\circ$ next to and above LOX- hole</td>
</tr>
<tr>
<td>16</td>
<td>1.2</td>
<td>-1.6</td>
<td>$R \approx 2.75m, \theta \approx 315^\circ$ around LOX- hole</td>
</tr>
<tr>
<td>17</td>
<td>1.8</td>
<td>-1.3</td>
<td>upper corner LOX- hole $R \approx 2.75m, \theta \approx 310^\circ$</td>
</tr>
<tr>
<td>18</td>
<td>1.4</td>
<td>-0.8</td>
<td>next to LOX- hole, $R = 2.75m, \theta = 280^\circ$ large areas $\theta \approx 200^\circ$ and $\theta \approx 330^\circ$</td>
</tr>
</tbody>
</table>

Table 6.11: Displacements for load cases group 10, DEROAH 3 s
### Table 6.12: Displacements for load cases group 20, VROOA H 75.5 s

<table>
<thead>
<tr>
<th>load case</th>
<th>$u_{\phi,\text{max}}$ [mm]</th>
<th>area where it occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>1.6</td>
<td>$R \approx 2.75m$, $\theta \approx 320^\circ$</td>
</tr>
<tr>
<td></td>
<td>-2.5</td>
<td>next to LOX-hole, $R = 2.75m$, $\theta = 280^\circ$</td>
</tr>
<tr>
<td>23</td>
<td>0.6</td>
<td>next to and above LOX-hole</td>
</tr>
<tr>
<td></td>
<td>-0.4</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td>25</td>
<td>1.4</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td></td>
<td>-2.1</td>
<td>$R \approx 2.75m$, next to LOX-hole</td>
</tr>
<tr>
<td>27</td>
<td>1.0</td>
<td>next to and above LOX-hole</td>
</tr>
<tr>
<td></td>
<td>-0.6</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
</tbody>
</table>

### Table 6.13: Displacements for load cases group 30, EPSYAH 107 s

<table>
<thead>
<tr>
<th>load case</th>
<th>$u_{\phi,\text{max}}$ [mm]</th>
<th>area where it occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>1.5</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td></td>
<td>-2.3</td>
<td>next to LOX-hole, $R = 2.75m$, $\theta = 280^\circ$</td>
</tr>
<tr>
<td>33</td>
<td>0.34</td>
<td>next to and above LOX-hole</td>
</tr>
<tr>
<td></td>
<td>-0.21</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td>35</td>
<td>1.3</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td></td>
<td>-1.9</td>
<td>$R \approx 2.75m$, next to LOX-hole</td>
</tr>
<tr>
<td>37</td>
<td>0.8</td>
<td>next to and above LOX-hole</td>
</tr>
<tr>
<td></td>
<td>-0.44</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
</tbody>
</table>

### Table 6.14: Displacements for load cases group 40, EPDIATI 118.5 s

<table>
<thead>
<tr>
<th>load case</th>
<th>$u_{\phi,\text{max}}$ [mm]</th>
<th>area where it occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>1.5</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td></td>
<td>-2.3</td>
<td>next to LOX-hole, $R = 2.75m$, $\theta = 280^\circ$</td>
</tr>
<tr>
<td>43</td>
<td>0.34</td>
<td>next to LOX-hole, $R = 2.75m$, $\theta = 280^\circ$</td>
</tr>
<tr>
<td></td>
<td>-0.21</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td>45</td>
<td>1.3</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
<tr>
<td></td>
<td>-1.9</td>
<td>next to LOX-hole, $R = 2.75m$, $\theta = 280^\circ$</td>
</tr>
<tr>
<td>47</td>
<td>0.8</td>
<td>next to and above LOX-hole</td>
</tr>
<tr>
<td></td>
<td>-0.44</td>
<td>$R \approx 2.75m$, $\theta \approx 315^\circ$</td>
</tr>
</tbody>
</table>
Nonlinear analysis

Load is incremented in three subcases. Load magnitude is controlled by imposing vertical displacement at the centre cardan. Transverse load at the VAO however is controlled by magnitudes of force. Both vertical displacement and VAO force are increased simultaneously. They are independent however. Since the structure behaves in a nonlinear way at elevated load levels, reaction force and transverse force do not always have a constant ratio. Output is requested only at the last increment of a subcase, in order to keep database and output files of reasonable size. For the last subcase however, full output is requested. Load incrementation scheme is shown in table 6.15. The fourth column is the load factor for the transverse load.

<table>
<thead>
<tr>
<th>subcase #</th>
<th>increments #</th>
<th>max. displacement [mm]</th>
<th>VAO load factor</th>
<th>intermediate output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>20</td>
<td>3</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>30</td>
<td>4.5</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>40</td>
<td>6</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 6.15: Load incrementation scheme for load case EPSYAHVAO

When incremental rotations are too large, the bisection method is activated and the load incrementation scheme is modified. Table 6.16 lists how the solution procedure evolves. The last column gives the number of iterations that are needed before convergence is achieved. Figure 6.9 displays the load–displacement curve.

Since this model represents half a cone, vertical reaction force that is computed in nonlinear analysis has to be multiplied by a factor of 2 to obtain total motor load. The horizontal line indicates limit load in the baseline load case with an engine thrust of 1.167 MN. In this load case, collapse load is:

\[ 2 \times 2.505MN = 5.009MN \]

Margin of safety is then:

\[ MS = \frac{5.009}{1.167} - 1 = 3.293 \]

Transverse load and vertical load are not proportional to each other, so transverse load has a different margin of safety:

\[ MS = 4.575 - 1 = 3.575 \]

The deformation pattern that corresponds to the collapse load is shown in fig. 6.10. The access hatch area is still most critical. Transverse load on VAO does not seem to have an effect on the collapse mode. There is no mutual influence between both parts of the general deformation pattern.
Figure 6.9: Load–displacement curve for load case EPSYAHVAO

Figure 6.10: Collapse mode for load case EPSYAHVAO, $MS = 3.293$
Table 6.16: Modified load incrementation scheme for load case EPSYAH VAO

6.3.5 Load case VROOH130

It is seen that transverse load on the centre cardan has a significant effect on collapse load. At time 75.5 s, temperature has risen. The combined effect of transverse load and reduced material properties may cause collapse load to drop.

Load is incremented in three subcases. Load magnitude is controlled by imposing vertical displacement at the centre cardan. Transverse load at the centre cardan however is controlled by magnitudes of force. Both vertical displacement and transverse force are increased simultaneously. They are independent however. Since the structure behaves in a nonlinear way at elevated load levels, reaction force and transverse force do not always have a constant ratio. Output is requested only at the last increment of a subcase, in order to keep database and output files of reasonable size. For the last subcase however, full output is requested. Load incrementation scheme is shown in table 6.17. The fourth column is the load factor for the transverse load.

When incremental rotations are too large, the bisection method is activated and the load incrementation scheme is modified. Table 6.18 lists how the solution procedure evolves. The last column gives the number of iterations that are needed before
Table 6.17: Load incrementation scheme for load case VROOAH130

<table>
<thead>
<tr>
<th>subcase #</th>
<th>increments #</th>
<th>max. displacement [mm]</th>
<th>transverse load factor</th>
<th>intermediate output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>12.5</td>
<td>1.875</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>16.66</td>
<td>2.5</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>25</td>
<td>3.75</td>
<td>yes</td>
</tr>
</tbody>
</table>

Convergence is achieved. Figure 6.11 displays the load-displacement curve.

Table 6.18: Modified load incrementation scheme for load case VROOAH130

<table>
<thead>
<tr>
<th>subcase #</th>
<th>load increment</th>
<th>bisection</th>
<th>displacement [mm]</th>
<th>load [MN]</th>
<th>transverse load factor</th>
<th>iterations #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>no</td>
<td>1.5625</td>
<td>0.234375</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>no</td>
<td>3.125</td>
<td>0.48675</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>no</td>
<td>4.6875</td>
<td>0.703125</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>no</td>
<td>6.25</td>
<td>0.9375</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>no</td>
<td>7.8125</td>
<td>1.171875</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>no</td>
<td>9.375</td>
<td>1.40625</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>no</td>
<td>10.9375</td>
<td>1.640625</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>no</td>
<td>12.5</td>
<td>1.038</td>
<td>1.875</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>no</td>
<td>13.3333</td>
<td>2</td>
<td>7</td>
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</tr>
<tr>
<td></td>
<td>10</td>
<td>no</td>
<td>14.1666</td>
<td>2.125</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>no</td>
<td>15</td>
<td>2.25</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>no</td>
<td>15.8333</td>
<td>2.375</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>no</td>
<td>16.6666</td>
<td>1.352</td>
<td>2.5</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>no</td>
<td>18.3333</td>
<td>1.451</td>
<td>2.75</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>no</td>
<td>20</td>
<td>1.521</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>20.4166</td>
<td>1.532</td>
<td>3.0625</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>20.46875</td>
<td>1.532</td>
<td>3.0703125</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Since this model represents half a cone, vertical reaction force that is computed in nonlinear analysis has to be multiplied by a factor of 2 to obtain total motor load. The horizontal line indicates limit load in the baseline load case with an engine thrust of 1.167 MN. In this load case, collapse load is:

\[ 2 \times 1.532MN = 3.064MN \]

Margin of safety is then:

\[ MS = \frac{3.064}{1.167} - 1 = 1.625 \]

Transverse load and vertical load are not proportional to each other, so transverse load
has a different margin of safety:

\[ MS = 3.063 - 1 = 2.063 \]

The deformation pattern that corresponds to the collapse load is shown in fig. 6.12. The access hatch area is most critical.

### 6.3.6 Summary of results

Five independent load cases are run, each yielding a different collapse load and corresponding deformation mode. Figure 6.13 summarises all load–displacement curves, and table 6.19 summarises all margins of safety, calculated with respect to the nominal load level prescribed for that load case.

<table>
<thead>
<tr>
<th>load case</th>
<th>nominal load ([MN])</th>
<th>collapse load ([MN])</th>
<th>margin of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPSYAH</td>
<td>1.167</td>
<td>5.059</td>
<td>3.34</td>
</tr>
<tr>
<td>EPSYAH130</td>
<td>1.167</td>
<td>4.299</td>
<td>2.68</td>
</tr>
<tr>
<td>VROOAH</td>
<td>0.992</td>
<td>3.645</td>
<td>2.67</td>
</tr>
<tr>
<td>EPSYAHVAO</td>
<td>1.167</td>
<td>5.009</td>
<td>3.29</td>
</tr>
<tr>
<td>VROOAH130</td>
<td>0.992</td>
<td>3.064</td>
<td>2.09</td>
</tr>
</tbody>
</table>

Table 6.19: Summary of margins of safety

The area between both access hatches is invariably most critical. Loads on VAO do not seem to affect the deformation pattern at the access hatch. Transverse loads applied at the centre cardan seem to be most harmful to the structure. Load cases VROOAH and VROOAH130 have lowest margins of safety. It should be clear, however, that a very conservative assumption is made with respect to loading in these load cases. The direction of transverse loading either \(F_Y\) or \(F_Z\) is rotated so as to coincide with the plane of symmetry. By doing so, the most critical area is loaded even more in compression.

MSC Los Angeles has run the baseline load case with linear material properties (ref. [14]). They have found that the structure behaves in an almost perfectly linear way for load levels up to 6 times limit load. The comparison of yield stress at a particular load case to collapse load level at the same level leads to some remarkable conclusions. \(CL\) indicates collapse load.

- load cases \(EPSYAH \leftrightarrow EPSYAH130\)

\[
\frac{CL_{EPSYAH130}}{CL_{EPSYAH}} = \frac{4.299}{5.059} = 0.850 \approx 0.830 = \frac{303}{365} = \frac{F_{y,130^\circ C}}{F_{y,room}}
\]
Figure 6.11: Load–displacement curve for load case VROOAH130

Figure 6.12: Collapse mode for load case VROOAH130, $MS = 1.625$
Figure 6.13: Load–displacement curves for all load cases

- load cases VROOAH ↔ VROOAH130

\[
\frac{CL_{VROOAH130}}{CL_{VROOAH}} = \frac{3.064}{3.645} = 0.841 \approx 0.830 = \frac{303}{365} = \frac{F_{y,130^\circ C}}{F_{y,room}}
\]

The ratio of collapse loads for related load cases appears to be constant. Stiffness moduli of the material at room temperature and at 130°C differ by 8% though. This difference does not seem to have a major impact. The general conclusion is that the structure fails by excessive plastic deformation.

6.3.7 Some additional comments

The deformation patterns for each load case indicate which parts of the structure are most sensitive to overloading. Visual interpretation shows how the structure is expected
to behave when other load cases are applied. Other load circumstances may occur (section 3.2):

thermal gradient: temperature differences between the separate structure's assemblies cause initial shrinkage of the structure

booster bar loads: horizontal booster bar loads tend to ovalise the circular perimeter of the box assembly

gEometric imperfections: minor geometric imperfections may occur due to machining, they are probably most significant in the cone panels

Each of the effects listed causes some initial deformation in the structure. Lateral displacements are significantly higher in load case EPSYAHV AO. Figures 6.9 and 6.10 show that effects on collapse load are negligible.

6.4 Interpretation of results

This section summarises major results. It gives some comments on how results should be interpreted.

The goal of the present study is to find out whether:

- general collapse of the structure does not interfere with local effects,
- collapse of the engine frame is due to geometric nonlinearities or to material nonlinearities,
- computations with a linear model are reliable for load levels up to ultimate load.

Some assumptions are necessary.

6.4.1 Reliability of the finite element computations

A model is developed that is particularly suited for nonlinear analysis of the complete structure:

- all components that are expected to contribute to the nonlinear behaviour of the structure are included in the model
- any simplification that is considered necessary must be conservative
although the structure and load components are not symmetric, a 180° model is used; the LBS- side of the structure with $\theta$ running 225° → 45° is considered to be weaker due to the presence of holes

- the finite element mesh exhibits all details that are considered necessary: all unflanged stiffeners are included, for the cone and the box assemblies

- all load cases that are listed in the load case report ref. [4] are considered; next to the baseline load case, four major load cases are identified that require nonlinear analysis

- the major load conditions and circumstances are studied, conclusions are based on results for more severe load cases

This model is completely different from the BOSOR4- model that is used in the past (ref. [9]). BOSOR4- models explicitly assume axisymmetric behaviour and axisymmetric buckling modes. The present 180°- model studies the structural behaviour of components that are symmetric with respect to a plane. The BOSOR4- model is not used for verification purposes.

Local buckling phenomena can not be described with this model. This model is capable though of representing buckling modes with a half wavelength equal to the stiffener pitch. It is not the purpose of the present analysis to investigate local buckling. Local buckling is covered in Fokker Space & Systems BV stress notes. Results are summarised in the margins of safety summary (ref. [5]).

### 6.4.2 Evaluation of the collapse load

The purpose of this study was the investigation of the overall buckling behaviour of the structure. The main driver in the design of stiffened panels and the determination of panel thicknesses is the avoidance of local buckling of skin and stiffeners. Local buckling was investigated appropriately with simple formulas. They are reported in the summary margins of safety report (ref. [5]). General instability of the structure is more difficult to predict. Local buckling effects are not fatal to a stiffened structure, as it only reduces stiffness. General instability on the other hand leads to complete failure of the structure.

The result of this analysis is a collapse load and corresponding collapse mode. Local buckling effects are explicitly excluded from this analysis. Local buckling involves a panel width equal to the stiffener pitch. The general instability collapse mode involves a larger part of the structure. The wavelengths of all collapse modes (fig. 6.4, 6.6, 6.8, 6.10, 6.12) are larger than the stiffener pitch.

Visual interpretation of the collapse modes quickly shows that only a small portion of the complete structure fails. For each load case, the collapse mode is constant.
The corresponding load level depends on the applied combination of load components. Collapse modes do not represent general instability, but rather panel buckling modes. Load levels that correspond to general instability will be even higher than the values found here.

Collapse is caused by exceedance of material yield stress. The structure behaves in an almost perfectly linear way for load levels up to 2.5 times limit load.

With the assumptions that are considered to be conservative, margins of safety with respect to collapse of the complete assembly are computed. All margins exceed 2.0. The most critical load case involves transverse loading applied at the centre cardan. It occurs at flight event VROOAH with material properties at temperature 130°C. The margin of safety is 2.09. The most critical area of the structure is the cone panels' section between both access hatches.
Chapter 7

Conclusion

This report deals with a finite element analysis of the load carrying capacity of the main stage engine support structure of the Ariane 5 launcher. To this end several finite element models of the engine support were constructed with the finite element code MSC/NASTRAN. The calculations that were carried out concern the nonlinear behavior of these models under various loading conditions (which are based on the predicted launch scenario). These calculations determine the collapse load of the structure.

The results of this investigation predict failure of the engine support above the design load intensity with a comfortable margin. They confirm the expectation that the engine support will meet its required design strength capability.

The analysis shows that the structure behaves in an almost perfectly linear way for load levels up to 2.5 times limit load.

With the assumptions that are considered to be conservative, margins of safety with respect to collapse of the complete assembly are computed. All margins exceed 2.0.

The critical load case involves transverse loading applied at the centre cardan. It occurs at flight event VROAH with material properties at temperature 130°C. The margin of safety is 2.09. The most critical area of the structure is the cone panels' section between both access hatches.

In summary, the results of the calculations show that the engine support will not fail before or at the load that corresponds to the predicted design strength (which is based on conservative “local buckling” criteria). In all cases there was a comfortable margin of safety, exceeding 2 in all load cases. Considering the fact that the finite element models used represent many structural details, it is concluded that the structure will meet its strength specifications.
Appendix A

Model characteristics

This appendix briefly lists some numerical information on the consecutive models that are developed. Numbers of nodes and elements are given for models Qu5, Bc2 and Bcc, together with a list of boundary conditions.

A.1 Model Qu5

The most critical cone panels' section is enclosed between both access hatches (between reference axes Y and Z). This model is a 90° model of cone assembly panels only. Panels are stiffened in meridional and circular directions. All unflanged stiffeners and ring frames are included in the model. The model is shown in fig. A.1. Its properties are listed in table A.1.

This model does not include the cross assembly. The bottom edge of this model is constrained in radial direction only over an angle of 30°, between both side webs:

\[ u_r = 0 \quad \text{nodes} \quad 1113, \ldots, 1125 \]

The cross assembly lower cylinder is rather stiff with respect to vertical deformation. Vertical displacement of the bottom edge is constrained by multipoint constraints MPC:

\[ u_z, i = u_z, 1118 \quad \text{nodes} \quad 1106, \ldots, 1117, 1119, \ldots, 1130 \]

This model does not include the box assembly. The upper edge is constrained only in vertical direction. It is free to rotate around the perimeter of the circular upper edge.

\[ u_z = 0 \quad \text{nodes} \quad 4401, \ldots, 4436 \]

Two non-structural model properties reflect the presence of the box assembly, which provides resistance to circumferential straining of the perimeter:
Figure A.1: Model QU5 mesh
MODEL CHARACTERISTICS

<table>
<thead>
<tr>
<th>item</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORD2C</td>
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<tr>
<td>CORD2S</td>
<td>8</td>
</tr>
<tr>
<td>GRID</td>
<td>2,402</td>
</tr>
<tr>
<td>g-set dofs</td>
<td>14,412</td>
</tr>
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<td>37</td>
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<tr>
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<td>2,383</td>
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<td>CTRIA3</td>
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<td>m-set dofs</td>
<td>61</td>
</tr>
<tr>
<td>l-set dofs</td>
<td>14,072</td>
</tr>
</tbody>
</table>

Table A.1: Model properties QU5

- CR0D elements provide axial stiffness in the circumferential direction of the upper perimeter, their cross sectional area is about equal to the total cross section of the box assembly components.

- a multi point constraint MPC imposes a constant radial displacement of all points on the upper perimeter:

  \[ u_r,i = u_{r,4418} \quad \text{nodes} \quad 4401, \ldots, 4436 \]

The edges \( \theta = 0^\circ \) and \( \theta = 90^\circ \) have symmetry conditions. In cylindrical coordinate systems, they are expressed as:

\[ u_\theta = \alpha_r = \alpha_z = 0 \]

In spherical coordinate systems, they are expressed as:

\[ u_\theta = \alpha_R = \alpha_\phi = 0 \]

Load incrementation is controlled by imposing vertical displacement of the middle grid on the bottom edge of the panels \( u_r,1118 \).
MODEL CHARACTERISTICS

A.2 Model Bc2

The most critical section is enclosed between both access hatches (between reference axes Y and Z). This model is a 90° model of cone and box assemblies only. Panels are stiffened in meridional and circular directions. All unflanged stiffeners and ring frames are included in the model. The model is shown in fig. A.2. Its properties are listed in table A.2.

<table>
<thead>
<tr>
<th>item</th>
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</thead>
<tbody>
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</tr>
<tr>
<td>1-set dofs</td>
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</tr>
</tbody>
</table>

Table A.2: Model properties Bc2

This model does not include the cross assembly. The bottom edge of this model is constrained in radial direction only over an angle of 30°, between both side webs:

\[ u_r = 0 \quad \text{nodes} \quad 11113, \ldots, 11125 \]

The cross assembly lower cylinder is rather stiff with respect to vertical deformation. Vertical displacement of the bottom edge is constrained by multipoint constraints MPC:

\[ u_{z,i} = u_{z,11118} \quad \text{nodes} \quad 11106, \ldots, 11117, 11119, \ldots, 11130 \]

The upper edge is constrained only in vertical direction. It is free to rotate around the perimeter of the circular upper edge.

\[ u_z = 0 \quad \text{nodes} \quad 55801, \ldots, 55836 \]
Figure A.2: Model Bc2 mesh
MODEL CHARACTERISTICS

The edges $\theta = 0^\circ$ and $\theta = 90^\circ$ have symmetry conditions. In cylindrical coordinate systems, they are expressed as:

$$u_\theta = \alpha_r = \alpha_z = 0$$

In spherical coordinate systems, they are expressed as:

$$u_\theta = \alpha_R = \alpha_\phi = 0$$

Load incrementation is controlled by imposing vertical displacement of the middle grid on the bottom edge of the panels $u_{z,11118}$.

A.3 Model Bcc

The most critical half of the engine frame comprises LOX-hole and LBS-holes (enclosed between angles $\theta = 225^\circ$ and $\theta = 45^\circ$ measured from reference axis $Y$).

This model includes the cross assembly in a rather coarse grid. Grids on the cross assembly centre column are constrained to stay in the vertical plane of symmetry $\theta = 0^\circ$ or $\theta = 180^\circ$. Constraints have to be added for loading in the transverse direction. These load components are applied in the plane of symmetry. One degree of freedom should be constrained, namely sliding in the direction of the plane of symmetry. More than one constrained node is required, however. If only one node were constrained, it would take the entire reaction force, which equals 170 kN at one time limit load. At higher load levels, reaction force is higher. Applying such a force to one node causes excessive deformation at that node. Therefore, the constraint is applied at multiple nodes, by expressing that the average displacement over multiple nodes is zero. Constrained nodes are located on the upper edge (RIE interface). For the middle nodes ($\theta$ around $90^\circ$) the circumferential displacement is constrained:

$$\sum_{i=55846}^{55846} u_{\theta,i} = 0$$

This expression is translated to a multi point constraint MPC.

The upper edge is constrained only in vertical direction. It is free to rotate around the perimeter of the circular upper edge.

$$u_z = 0 \quad \text{nodes} \quad 55801, \ldots, 55872$$

The edges $\theta = 0^\circ$ and $\theta = 180^\circ$ have symmetry conditions. In cylindrical coordinate systems, they are expressed as:

$$u_\theta = \alpha_r = \alpha_z = 0$$
Figure A.3: Model BCC mesh
Table A.3: Model properties Bcc

In spherical coordinate systems, they are expressed as:

\[ u_\theta = \alpha_R = \alpha_\phi = 0 \]

Load incrementation is controlled by imposing vertical displacement of the centre cardan \( u_z,90000 \). Next to vertical displacements some force components are added in load cases VROOAH and EPSYAH+VAO.
Appendix B

Coordinate systems

B.1 General considerations

As a basic rule every node of the model is expressed in a coordinate system that represents the shape of the structure in the easiest way possible. Conical parts are described in a spherical coordinate system, cylindrical parts are described in a cylindrical system.

The basic coordinate system (no. 0) is rectangular. Its origin is located at the theoretical apex of the conical structure. The $X$, $Y$- and $Z$-axes point along the system axes introduced by Aerospatiale: the $X$-axis is the longitudinal axis of the launcher, the positive $Y$-axis points opposite to the SSHEL-sphere, the positive $Z$-axis points in the direction of the LH2-line. Every other coordinate system is defined with respect to the global coordinate system no. 0. They are all either spherical or cylindrical. Their respective axes of symmetry (local $z$-axis) coincide with the global $X$-axis.

Several reasons justify this particular selection of coordinate systems:

- the definition of grid point location is easy. The identification number of the coordinate system indicates which part of the structure the node is located in. Individual coordinates are independent, and sometimes constant for an important part of the structure, e.g. the azimuthal angle of all cone panels.

- interpretation of displacement quantities is straightforward, e.g. radial or azimuthal displacements are easier to interpret than cartesian displacements.

- eccentricities between different parts of the structure are described easily. Cone panels have a smooth outward surface. Differences in thickness are obtained by machining the inner side of the panels. This method inevitably introduces eccentric positions of the panels' neutral axis. MSC/NASTRAN allows the introduction of offsets at element boundaries. In geometrically nonlinear analysis however, large displacements occur and a linearised approach is no longer possible. Offsets
must not be used in non-linear analysis. It is expected that excentric positions of
a panel’s neutral axis introduce significant effects on load paths. Consequently,
bending moments are generated.

Only a limited number of panel thicknesses occur in the structure. Each panel
thickness has its own spherical coordinate system. The azimuthal angle of panels’
neutral axes being the same for all panels, the location of the origin of the coor-
dinate system determines the relative position of the panels’ neutral axes. The
identification number of the coordinate system is chosen equal to 10 times the lo-
cal panel thickness. Webs that stiffen the box assembly’s conical panels are on the
outside of the cone. The identification number of the corresponding coordinate
systems is equal to 100 plus 10 times the local panel thickness.

There is one exception however. In those areas where panel thickness changes
neutral axes are shifted with respect to each other. In those areas two nodes are
needed to represent geometry correctly. Only one node is defined however. It is
located on the neutral axis of the thicker of both panels. This representation is
not a perfect description of geometry. The area affected by this error is only small.
It is expected that the influence on load trajectories through the entire structure
is small.

Displacement results are always expressed in the same coordinate system that is used
for the definition of geometrical location of nodes.

B.2 List of spherical coordinate systems

- 1 the origin of this coordinate system coincides with the origin of the basic co-
ordinate system no. 0. The first coordinate is the distance of the node to the
theoretical apex of the cone. The second coordinate is the angle of the cone
(36.49°). The third coordinate is the circumferential angle. It is zero at the Y-
axis of the basic coordinate system.

- 2 all grids located in the cone panels radial unflanged stiffeners are defined in this
coordinate system. The origin of this system is located 51.3 mm above the origin
of the basic coordinate system no. 0. The first coordinate is the distance of the
node to the theoretical apex of the cone. The second coordinate is the angle of
the cone (36.49°). The third coordinate is the circumferential angle. It is zero at
the Y- axis of the basic coordinate system.

- 6 all grids located in the box assembly radial blade stiffeners are defined in this
coordinate system. The origin of this system is located 51.3 mm below the origin
of the basic coordinate system no. 0. The first coordinate is the distance of the
node to the theoretical apex of the cone. The second coordinate is the angle of
the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

- **7** all grids located in the middle panel at the the cone box connection are defined in this coordinate system. The origin of this system is located 1.68 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

- **21** all grids located in the conical panels that are 2.1 mm thick are defined in this coordinate system. The origin of this system is located 10.8 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

- **23** all grids located in the conical panels that are 2.3 mm thick are defined in this coordinate system. The origin of this system is located 10.7 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

- **33** all grids located in the conical panels that are 3.3 mm thick are defined in this coordinate system. The origin of this system is located 9.8 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

- **42** all grids located in the conical panels that are 4.2 mm thick are defined in this coordinate system. The origin of this system is located 9.1 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

- **50** all grids located in the conical panels that are 5.0 mm thick are defined in this coordinate system. The origin of this system is located 8.4 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.
• **60** all grids located in the conical panels that are 6.0 mm thick are defined in this coordinate system. The origin of this system is located 7.5 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

• **85** all grids located in the conical panels that are 8.5 mm thick are defined in this coordinate system. The origin of this system is located 5.5 mm below the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

• **123** all grids located in the box assembly conical panels that are 2.3 mm thick are defined in this coordinate system. The origin of this system is located 10.7 mm above the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

• **150** all grids located in the box assembly conical panels that are 5.0 mm thick are defined in this coordinate system. The origin of this system is located 8.4 mm above the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

• **160** all grids located in the box assembly conical panels that are 6.0 mm thick are defined in this coordinate system. The origin of this system is located 7.6 mm above the origin of the basic coordinate system no. 0. The first coordinate is the distance of the node to the theoretical apex of the cone. The second coordinate is the angle of the cone (36.49°). The third coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system.

### B.3 List of cylindrical coordinate systems

• **3** this coordinate system is used only as an output coordinate system. Constraints at the cross-cone connection are expressed in cylindrical coordinates. Radial displacements are constrained, and vertical displacements are imposed. The origin of this system is located in the horizontal plane through the lower cylinder interface, 1.182 m above the origin of the basic coordinate system no. 0. Displacement no.
1 is the horizontal component of the radial displacement. Displacement no. 2 is measured in circumferential direction, and displacement no. 3 is measured in vertical direction.

- 4 all grids located at the level of the solid propellant booster rod connection bearings are defined in this coordinate system. The origin of this system is located 3.229 m above the origin of the basic coordinate system no. 0. The first coordinate is the horizontal component of the radial distance of the node to the axis of symmetry. The second coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system. The third coordinate is measured in the vertical direction, with respect to the origin of the local system. Output displacements for all box assembly grids are given in this coordinate system.

- 5 all grids located at the level of the box floor are defined in this coordinate system. The origin of this system is located 3.2307 m above the origin of the basic coordinate system no. 0. The first coordinate is the horizontal component of the radial distance of the node to the axis of symmetry. The second coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system. The third coordinate is measured in the vertical direction, with respect to the origin of the local system. Output displacements for all box assembly grids are given in this coordinate system.

- 11 all grids located in the lower of the three intermediate ring frames are defined in this coordinate system. The origin of this system is located 1.5745 m above the origin of the basic coordinate system no. 0. The first coordinate is the horizontal component of the radial distance of the node to the axis of symmetry. The second coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system. The third coordinate is measured in the vertical direction, with respect to the origin of the local system.

- 12 all grids located in the middle of the three intermediate ring frames are defined in this coordinate system. The origin of this system is located 1.8435 m above the origin of the basic coordinate system no. 0. The first coordinate is the horizontal component of the radial distance of the node to the axis of symmetry. The second coordinate is the circumferential angle. It is zero at the Y-axis of the basic coordinate system. The third coordinate is measured in the vertical direction, with respect to the origin of the local system.

- 13 all grids located in the top of the three intermediate ring frames are defined in this coordinate system. The origin of this system is located 2.6235 m above the origin of the basic coordinate system no. 0. The first coordinate is the horizontal component of the radial distance of the node to the axis of symmetry. The second coordinate is the circumferential angle. It is zero at the Y-axis of the basic
coordinate system. The third coordinate is measured in the vertical direction, with respect to the origin of the local system.

### B.4 List of rectangular coordinate systems

The basic coordinate system no. 0 is rectangular.

- **91** the structure which is used as a reinforcement to the LOX hole consists of two beamlike components that the upper intermediate ring frame to the middle ring frame. Each component is described in its own coordinate system. System no. 91 is located on the SSHEL-side of the LOX-hole. Unlike the other coordinate systems it is not defined with respect to the basic coordinate system no. 0. It is defined by reference to cylindrical coordinate system no. 12. The origin is located in the tip of the middle intermediate ring frame, 1.8435 m above the origin of the basic coordinate system no. 0. The z- axis is parallel to the axis of symmetry of the launcher. The x- axis is in radial direction, at an angle of 216.75° with respect to the Y- axis of the basic coordinate system. The Y- axis is in tangential direction.

- **92** the structure which is used as a reinforcement to the LOX hole consists of two beamlike components that the upper intermediate ring frame to the middle ring frame. Each component is described in its own coordinate system. System no. 92 is located on the GAM-side of the LOX-hole. Unlike the other coordinate systems it is not defined with respect to the basic coordinate system no. 0. It is defined by reference to cylindrical coordinate system no. 12. The origin is located in the tip of the middle intermediate ring frame, 1.8435 m above the origin of the basic coordinate system no. 0. The z- axis is parallel to the axis of symmetry of the launcher. The x- axis is in radial direction, at an angle of 233.25° with respect to the Y- axis of the basic coordinate system. The Y- axis is in tangential direction.
Appendix C

Conventions in node and element numbering

Numbering schemes are chosen in a transparant way. The structure is more or less axisymmetric. Cross sections of the structure with either a horizontal or a cylindrical surface on the one hand and a vertical plane through the axis of symmetry on the other hand have constant numbers. Nodes describing stiffeners have identification numbers related to the identification numbers of the corresponding node on the main structure. In this way, reference to a certain node anywhere on the structure is relatively easy for models as large as the present models.

C.1 Node numbering

In model QU5, all node and element numbers are less than 10000. The first and the second digits indicate in which circular cross section the node is located (00 < xx < 37):

11xx : interface with cross assembly
nnxx : intermediate cross sections (12 < nn < 43)
44xx : interface with box assembly
53xx to 82xx : nodes on unflanged stiffeners, node mmxx corresponds node nnxx on main structure with nn = mm − 40
91xx to 93xx : lower ring frame
94xx to 96xx : middle ring frame
97xx to 99xx : upper ring frame

The last two digits range from 00 to 37:

xx00 : node located at the plane of symmetry θ = 0°
**NUMBERING CONVENTIONS**

$xxnn$ : node located at the plane $\theta = 2.5^\circ nn - 1.25^\circ$

$xx37$ : node located at the plane of symmetry $\theta = 90^\circ$

In models BC2 and BCC, all node and element numbers are less than 100000. The first digit indicates the part of the structure where the node is located:

1$xxxx$ : node located in the cone panels
2$xxxx$ : node located in the box floor
3$xxxx$ : node located in the box conical panels
4$xxxx$ : node located in the box cylinder panels
5$xxxx$ : node located in the top interface ring
6$xxxx$ : node located in one of the box radial webs
7$xxxx$ : node located in one of the three intermediate ring frames
8$xxxx$ : node located in the lower cylinder (cross assembly)
9$xxxx$ : node located in the cross assembly (for load introduction only) or in the LOX-hole reinforcement beams

In model BC2, the second and the third digits indicate in which circular cross section the node is located ($00 < xx < 37$):

101$xx$ to 137$xx$ : cone panels
153$xx$ to 184$xx$ : nodes on unflanged stiffeners, node 1$mmxx$ corresponds to node 1$nnxx$ on main structure with $nn = mm - 50$
244$xx$ to 251$xx$ : box floor
288$xx$ to 291$xx$ : nodes on unflanged stiffeners, node 2$mmxx$ corresponds to node 2$nnxx$ on main structure with $nn = mm - 40$
345$xx$ to 352$xx$ : box assembly conical panels
388$xx$ to 391$xx$ : nodes on unflanged stiffeners, node 3$mmxx$ corresponds to node 3$nnxx$ on main structure with $nn = mm - 40$
452$xx$ to 454$xx$ : box assembly cylindrical panels
556$xx$ to 558$xx$ : top interface ring
611$xx$ to 612$xx$ : box assembly radial webs
711$xx$ to 713$xx$ : lower ring frame
721$xx$ to 723$xx$ : middle ring frame
731$xx$ to 733$xx$ : upper ring frame
801$xx$ to 809$xx$ : lower cylinder

In model BCC the second and the third digits indicate in which circular cross section the node is located ($00 < xx < 73$):

101$xx$ to 137$xx$ : cone panels
153$xx$ to 184$xx$ : nodes on unflanged stiffeners, node 1$mmxx$ corresponds to
NUMBERING CONVENTIONS

node \(1nnzx\) on main structure with \(nn = mm - 50\)

244zx to 251zx : box floor

288zx to 291zx : nodes on unflanged stiffeners, node \(2mmzx\) corresponds to
node \(2nnzx\) on main structure with \(nn = mm - 40\)

345zx to 352zx : box assembly conical panels

388zx to 391zx : nodes on unflanged stiffeners, node \(3mmzx\) corresponds to
node \(3nnzx\) on main structure with \(nn = mm - 40\)

452zx to 454zx : box assembly cylindrical panels

556zx to 558zx : top interface ring

611zx to 612zx : box assembly radial webs

711zx to 713zx : lower ring frame

721zx to 723zx : middle ring frame

731zx to 733vx : upper ring frame

801zx to 809zx : lower cylinder

Model BCC have holes in the cone assembly panels. The upper and lower borders are
stiffened with increased panel thicknesses. The width of the stiffened area is small,
typically 10 to 25 \(mm\). Some additional elements and nodes are required to accurately
represent this geometry. Nodes and corresponding elements have numbers 141zx to
147zx for main structure, and 191zx to 197zx for unflanged stiffeners.

In model BC2, the last two digits range from 00 to 37 :

\(xx00\) : node located at the plane of symmetry \(\theta = 0^\circ\)

\(xxnn\) : node located at the plane \(\theta = 2.5^\circ nn - 1.25^\circ\)

\(xx37\) : node located at the plane of symmetry \(\theta = 90^\circ\)

In model BCC, the last two digits range from 00 to 73 :

\(xx00\) : node located at the plane of symmetry \(\theta = 0^\circ\)

\(xxnn\) : node located at the plane \(\theta = 2.5^\circ nn - 1.25^\circ\)

\(xx73\) : node located at the plane of symmetry \(\theta = 180^\circ\)

Nodes with identifications 90000 and above do not obey this rule.

C.2 Element and property numbering

Element numbering strategies are similar to node numbering strategies. Each element
on the main structure has an identification number that corresponds to the identification
of an adjacent node. Elements on the cone assembly panels have the identification
number of the lower of both circular edges and the upper of both vertical cross sections. Elements on the unflanged stiffeners have identification numbers equal to the identification number of the lower of both stiffener nodes.

A plate element property identification is equal to 10 times the plate thickness expressed in mm. There is one exception however, plate elements at the top cylinder interface have thicknesses that vary through the element from 6.7 mm to 14 mm. Element property no. 100 has a thickness of 10 mm associated to it. Bending stiffnesses are multiplied by a factor of 350 to account for the interspacing between panels.

All beam element property identifications are greater than 2000.
Appendix D

Parameter settings in
MSC/NASTRAN

MSC/NASTRAN provides two solution procedures for nonlinear analysis. This appendix briefly shows how parameters select algorithm options.

D.1 Incremental nonlinear procedures

The incremental procedure increases the load value with a constant increment. Parameters that define when convergence is reached are set on the bulk data entry NLPARM:

<table>
<thead>
<tr>
<th>NLPARM</th>
<th>ID</th>
<th>INC</th>
<th>DT</th>
<th>KMETHOD</th>
<th>KSTEP</th>
<th>MAXITER</th>
<th>CONV</th>
<th>INTOUT</th>
<th>EPSU</th>
<th>EPSP</th>
<th>EPSW</th>
<th>MAXDIV</th>
<th>MAXQN</th>
<th>MAXLS</th>
<th>FSTRESS</th>
<th>LSTOL</th>
<th>MAXBIS</th>
<th>MAXR</th>
<th>RTOLB</th>
</tr>
</thead>
</table>

- ID is the identification number of the nonlinear parameter set, that is selected in the case control deck
- INC is the number of load increments in a particular subcase
- DT is not used here
- KMETHOD selects the procedure of updating stiffness matrices:
  - AUTO: automatic procedure, computation of new stiffness matrix only when KSTEP iterations are performed
  - ITER: no automatic update of stiffness matrix, computation of stiffness matrix every times KSTEP iterations are performed
- **SEMI**: An intermediate procedure of updating the stiffness matrix

- **KSTEP** is the number of iterations that has to be performed before a new stiffness matrix is computed.

- **MAXITER** is the maximum number of iterations allowed per load increment.

- **CONV** selects which convergence criteria must be met before the next load increment is started:
  - **U** is the criterion based on displacements
  - **P** is the criterion based on residual forces
  - **W** is the criterion on a combined effect of displacements and residual forces

- **INTOUT** selects which output requests are active.

- **EPSU** sets the tolerance for convergence in the **U** criterion.

- **EPSP** sets the tolerance for convergence in the **P** criterion.

- **EPSW** sets the tolerance for convergence in the **W** criterion.

- **MAXDIV** sets the limit on probable divergence conditions per iteration before stiffness update.

- **MAXQN** is the maximum number of Quasi-Newton correction vectors.

- **MAXLS** is not used.

- **FSTRESS** is not used.

- **LSTOL** is not used.

- **MAXBIS** is the maximum number of bisections allowed for each load increment.

- **MAXR** is the maximum ratio for the adjusted-length increment relative to the initial value.

- **RTOLB** is the maximum value of incremental rotation allowed per iteration to activate bisection.
D.2 Path following procedures

Path following procedures adjust the load increment automatically. They increase the load factor until collapse is reached. Parameters that compute the load increment through the bulk data entry NLPCI. This entry is always complementary to an NLPARM entry with the same identification.

<table>
<thead>
<tr>
<th>NLPCI</th>
<th>ID</th>
<th>TYPE</th>
<th>MINALR</th>
<th>MAXALR</th>
<th>SCALE</th>
<th>DESITER</th>
<th>MXINC</th>
</tr>
</thead>
</table>

- **ID** is the identification number of the nonlinear parameter set, that is selected in the case control deck
- **TYPE** selects the path following strategy
- **MINALR** is the minimum factor for adjusting the arc length on the path following procedure
- **MAXALR** is the maximum factor for adjusting the arc length on the path following procedure
- **SCALE** is the scale factor for controlling the loading condition in the arc-length constraint
- **DESITER** is the desired number of iterations per increment before convergence is reached
- **MXINC** is the maximum number of iterations in a subcase to reach collapse load

Path following procedures are not used in this study. In the incremental method, the final load is subdivided in a number of subcases. Each subcase has a particular maximum load, and a number of increments before the maximum is reached. For each increment, convergence has to be reached before the next increment is initiated. Unless convergence is obtained after a number of iterations that is less than the parameter MAXITER, the analysis stops.

D.3 Material properties

Two separate entries are used to describe the linear and nonlinear material characteristics:

<table>
<thead>
<tr>
<th>MAT1</th>
<th>MID</th>
<th>E</th>
<th>G</th>
<th>NU</th>
<th>RHO</th>
<th>A</th>
<th>TREF</th>
<th>GE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST</td>
<td>SC</td>
<td>SS</td>
<td>MCSID</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**MAT1** defines the material properties for linear, temperature-independent isotropic material:

- **MID** is the material identification number. In the present analyses it is constant because the entire structure is made of a single material
- **E** is the modulus of elasticity
- **G** is not used here
- **NU** is POISSON’s ratio
- **RH0, A, TREF, GE, ST, SC, SS, MCSID** are not used here

**MATS1**

<table>
<thead>
<tr>
<th>MID</th>
<th>TID</th>
<th>TYPE</th>
<th>H</th>
<th>YF</th>
<th>HR</th>
<th>LIMIT1</th>
<th>LIMIT2</th>
</tr>
</thead>
</table>

**MATS1** specifies material properties which are stress dependent for use in material nonlinearity applications. It is activated in conjunction with a **MAT1** entry that has the same **MID** value.

- **MID** is the material identification number
- **TID** is not used here
- **TYPE** is the type of material nonlinearity
- **H** is the work hardening slope
- **YF** defines the yield criterion:
  1. **VON MISES**, (→ default)
  2. **TRESCA**
  3. **MOHR–COULOMB**
  4. **DRUCKER–PRAGER**
- **HR** defines the hardening rule:
  1. isotropic, (→ default)
  2. kinematic
  3. combined
- **LIMIT1** defines the yield stress
- **LIMIT2** is not used here