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National Aerospace Laboratory NLR

NLR-TP-2001-150

Design and optimisation of an Ariane LOX line cover

Use of IDL in B2000

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Summary

In June 2000 a two-year joint programme by Fokker Space (FS), Centre of Lightweight Structures (CLC), and the National Aerospace Laboratory NLR was started to develop, manufacture, and qualify a demonstrator fairing. The programme is funded by the Netherlands Agency for Aerospace Programmes (NIVR) within the framework of the national NRT programme. Within the joint programme NLR contributed to the preliminary design and was responsible for the design optimisation. The design optimisation was performed with the B2000 code.

In the preliminary design phase the loads on, and the requirements for, the Liquid Oxygen (LOX) fairing were investigated. Different options were considered for materials, manufacturing processes and design concepts. Trade-offs supported by preliminary analyses showed that a CFRP stiffened skin concept in combination with Vacuum Assisted Resin Transfer Moulding (VARTM) technology was the most promising concept in terms of cost reduction, weight reduction and possibilities to use the same concept for other fairings as well.

For the design optimisation, first the LOX fairing was discretised into a FEM analysis model. This has been done manually using the Input Description Language (IDL) of the B2000 code. Using this scripting language it is possible to build the model in substructures. Also loads, boundary conditions and materials were translated into B2000 FEM-format. Next, a FEM optimisation model was made. The optimisation model describes which design parameters may vary, which conditions should be met, and how the search for better designs is controlled. The description was done manually using the Optimisation Model Input Description Language (OMIDL) of the B2000 code. The same kind of structuring has been used as for the analysis model.

Several initial designs, each with a different number of stiffeners, have been analysed and optimised, resulting in a range of optimised designs, from which one design has been selected and analysed in detail. This design is the result of analyses and optimisations with estimated material properties. B-basis allowables will become available from a test programme, which will be completed in the beginning of 2001. The B-basis allowables will be used in a new set of optimisations and analyses, resulting in a final design. This design, which will be further detailed and analysed (e.g. connections), will result in the issue of production drawings of a mould and of a full scale fairing demonstrator in the year 2001.

Contents

(32 pages in total)

List of Abbreviations

CFRP	Carbon Fibre Reinforced Plastics
CLC	Centre of Lightweight Structures
DOF	Degree Of Freedom
DUL	Design Ultimate Load
DV	Design Variable
FEM	Finite Element Model
FS	Fokker Space
GFRP	Glass Fibre Reinforced Plastics
IDL	Input Description Language
LOX	Liquid Oxygen
NIVR	Netherlands Agency for Aerospace Programmes
NLR	National Aerospace Laboratory
OMIDL	Optimization Model Input Description Language
VARTM	Vacuum Assisted Resin Transfer Moulding

List of Symbols

C_{ij}	component in linking matrix
f_n	natural frequency
K	global stiffness matrix
$K_{,x}$	global stiffness gradient
k	stiffness
MP^i	i'th Model Parameter
m	mass
P	global force vector
$P_{,x}$	global force gradient
TH	Tsai-Hill criterion
U	global displacement vector
$U_{,x}$	global displacement gradient
x^j	j'th Design Variable
σ	normal stress
$\overline{\sigma}$	allowable normal stress
τ	shear stress
$\overline{\tau}$	allowable shear stress

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1 Introduction

Fokker Space (FS) is a European supplier of launcher structural systems. FS has been collaborating on the development of the Ariane 5 launch vehicle (see Fig. 1). However, for the

Fig. 1 The Ariane 5 launch vehicle

traditional expendable launch vehicles, commercial competition is increasing with the associated demand for dramatic cost reductions. Arianespace is looking for a substantial reduction in recurring costs. A great deal of cost reduction can be achieved by design optimisation. However, it is recognised that additional savings can be realised by the introduction of new manufacturing technologies. A survey on the components and assemblies of the main engine frame of Ariane 5 indicated, that significant savings can be achieved on the fairings over the fuel lines through the introduction of a composite production process. The current fairings are made out of formed, stiffened and riveted aluminium sheet. The manufacturing process is labour intensive and hence costly. FS proposes to replace these metal assemblies by composite components with a high level of part integration. The aim is to reduce the recurring costs by 50%. Reduction of weight is not a requirement, but the composite fairings should not become heavier than the current metal fairings. Three fairings are covering the LOX line (see Fig. 2). It was decided to redesign the upper LOX line cover, because it is the most complex of the three fairings.

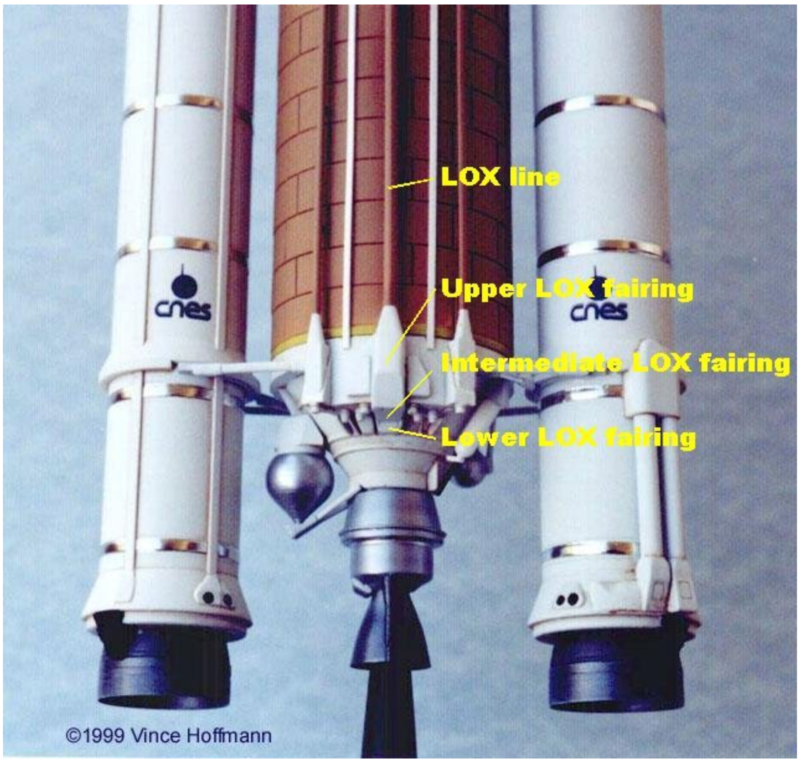

Fig. 2   Fairings on the Ariane 5

In June 2000 a two-year joint programme by Fokker Space, Centre of Lightweight Structures (CLC), and the National Aerospace Laboratory NLR was started to develop, manufacture and qualify a demonstrator fairing. The programme is sponsored by the Netherlands Agency for Aerospace Programmes (NIVR) within the national NRT programme. Within the joint programme NLR contributed to the preliminary design and was responsible for the design optimisation. The design optimisation has been performed with B2000 (Ref. 1- 5).

2 Loads on the LOX line cover

During flight, different mission phases, each with their own loads, can be distinguished. During mission phase 1 (ignition) only acoustic loads occur. During mission phase 2 (at take-off) blast wave loads and acoustic loads occur. During mission phase 3 (atmospheric flight) acoustic loads and aerodynamic loads occur. These loads have been converted by FS to static pressure loads for the dimensioning of the LOX fairings. For the acoustic loads two load levels during atmospheric flight can be distinguished. When the eigenfrequency of the LOX fairing is high enough, considerably lower pressure loads can be applied. The dimensioning loads during the optimisation were the combined acoustic and aerodynamic loads. An ultimate safety factor equal to 1.25 shall be applied to these limit mechanical loads for dimensioning with respect to failure of the LOX fairing.

In addition to the pressure loads, a thermal load has been defined. Therefore, the LOX fairing is covered with a layer of thermal protection. The peak temperature of the skin under the layer of thermal protection is found to be approximately 147^oC.

3 Design requirements

3.1 Geometrical requirements

The composite fairing should have the same interfaces as the aluminium fairing, with the exception of a support rig in the tapered section of the fairing. This support rig can be redesigned if necessary. Alterations to the outer geometry of the fairing are allowed, but the new composite upper fairing should not exceed the envelope of the current metallic structure too much. Further, a stay-out zone at the inside of the fairing has been defined where the LOX line is placed. This restricts the geometry of the composite fairing in such a way that only small variations are possible. The geometry of the composite fairing will be very similar to the aluminium fairing.

3.2 Stress requirements

Failure of the structure is not allowed below Design Ultimate Load. As stress failure criterion the Tsai-Hill criterion has been chosen:

$$TH = \sqrt{\left(\frac{\sigma_1}{\overline{\sigma}_1}\right)^2 + \left(\frac{\sigma_2}{\overline{\sigma}_2}\right)^2 - \frac{\sigma_1 \cdot \sigma_2}{\overline{\sigma}_1 \cdot \overline{\sigma}_2} + \left(\frac{\tau_{12}}{\overline{\tau}_{12}}\right)^2}$$

3.3 Buckling requirements

Local buckling should not occur below limit load. Global buckling of the structure should not occur below ultimate load.

3.4 Eigenfrequency requirements

No actual requirement has been defined for the eigenfrequency of the structure. However, when the natural frequency is high enough ($f_n > 176.8Hz$) the acoustic loads during atmospheric flight become considerably lower. Therefore, two different design methods can be used:

1. Use "heavy loads" for calculation of stresses, do not apply constraint on eigenfrequency.
2. Use "light loads" for calculation of stresses, apply constraint on eigenfrequency.

The optimisation will show which design is preferred.

For the calculation of the eigenfrequency the influence of the thermal protection has to be taken into account. It is assumed that the thermal protection does not contribute to the stiffness (and strength) of the structure. However, the mass of the thermal protection cannot be neglected. The eigenfrequency varies approximately linearly with $\sqrt{\frac{k}{m}}$ in which k is the stiffness and m is the mass. As the contribution of mass of the thermal protection can be up to 50% of the total mass, the eigenfrequency of the structure can be reduced with 30%.

4 Preliminary design, the different design concepts

In the preliminary design phase three different design concepts were considered:

1. A sandwich construction with CFRP/GFRP facings and foam core produced by vacuum prepreg.
2. A CFRP/GFRP single skin produced by Vacuum Assisted Resin Transfer Moulding (VARTM) or vacuum prepreg.
3. A CFRP/GFRP stiffened skin produced by VARTM or vacuum prepreg.

Trade-offs supported by preliminary analyses showed that the CFRP stiffened skin in combination with VARTM was the most promising concept in terms of cost reduction, weight reduction and possibilities to use the same concept for other fairings as well. Because of the high operating temperatures of the fairing, a resin system with a sufficiently high T_g ($\pm 200^oC$) has been chosen. This resin system is relatively expensive, making the total costs of the fairing strongly dependent of the amount of material used (and thus of the structural mass of the fairing).

The current metallic fairing is composed of a prismatic section and a tapered section (see Fig. 3). In the preliminary design it was recognised that the sharp corners in the tapered section are a

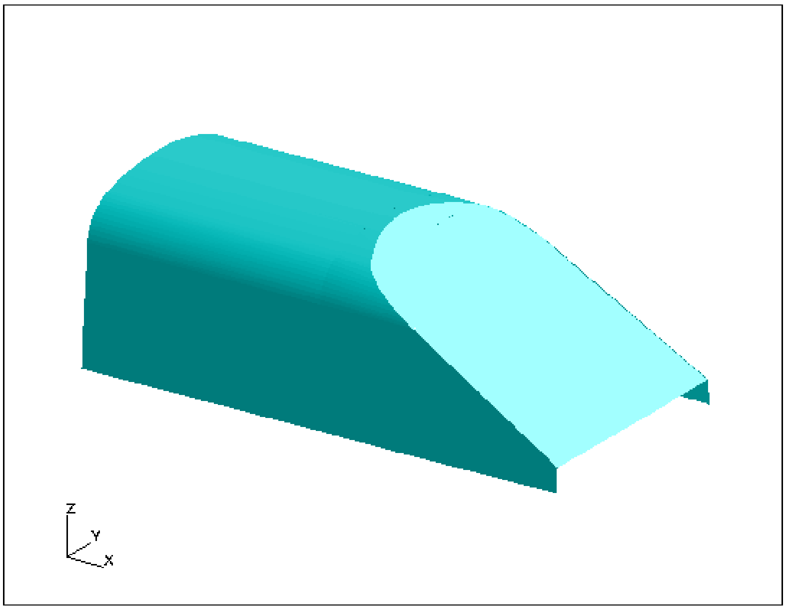

Fig. 3 The outer geometry of the current metallic upper LOX fairing

problem area in terms of stresses and in terms of manufacturing. Therefore, a new geometry has been designed (see Fig. 4) which slightly exceeds the envelope of the metallic fairing. As stiffener

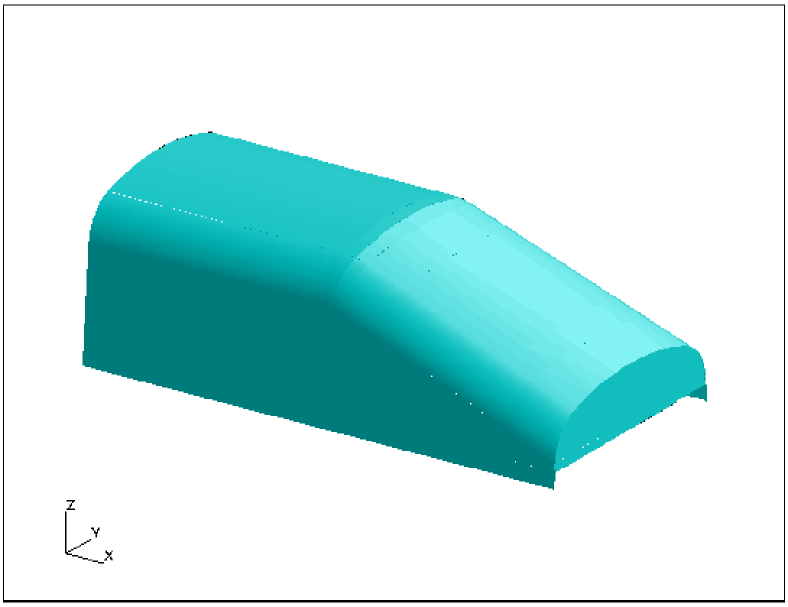

Fig. 4 The outer geometry of the composite upper LOX fairing

concept, hat-stiffeners were chosen (see Fig. 5). The sides of the stiffeners only contain angle plies ($\pm 45^o$ fabric). Extra longitudinal plies are placed in the top of the stiffener ($0^o/90^o$ fabric). The skin only contains the $0^o/90^o$ fabric. The fabric is a 2x2 Twill with an equal amount of tows in warp and weft direction. The 0^o direction is in the longitudinal direction of the stiffener.

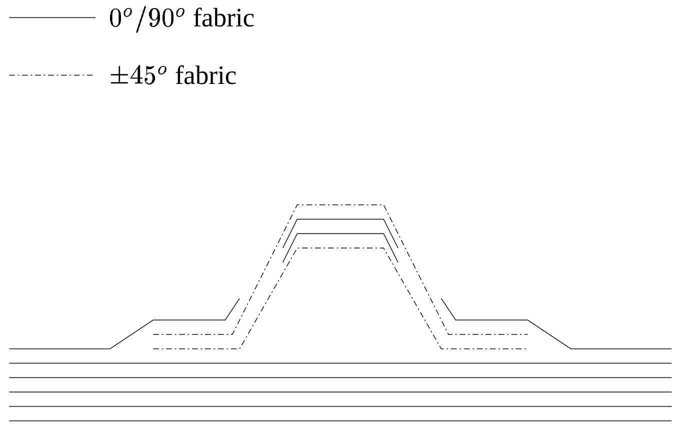

Fig. 5 The hat-stiffener concept

At the edges of the fairing the stiffeners will have to end. To compensate for the loss of bending stiffness, extra longitudinal plies will be added to the skin. Further, extra angle plies will be added to the skin to increase the bearing strength (the edges are bolted to the main stage engine thrust frame). These extra plies start at the edge of the fairing and run underneath the stiffener to a certain extent. Extra angle plies will be added to the end of the stiffener as well to create a load path from the top of the stiffener to the skin.

5 The analysis model

The structure of the LOX line cover, defined in the previous chapter, is discretised into a FEM analysis model . This has been done manually using the advanced ”Input Description Language” (IDL) of the B2000 code (Ref. 4). Using this scripting language it is possible to build the model in substructures. The model is almost completely parametrised. A few patches in the model had to be imported from Patran, which has more possibilities for modelling and meshing. The parametrisation enables quick changes within the model, such as number of stiffeners, width and height of the stiffeners, lay-up and mesh density of the LOX fairing. Also loads, boundary conditions and materials are translated into B2000 FEM-format.

The entire model is split up in different files, each file modelling a different part of the structure, i.e., skin prismatic section, stringer prismatic section, skin tapered section, stringer tapered section, etc. These substructures are split up again in sub-substructures, i.e., stringer foot, stringer top, etc. The B2000 input processor handles these files as a kind of subroutines in a computer code. There is a ”main programme” (the file ’LOX.inp’) which calls all the other components. The different parameters used in the model, are defined and explained in a file called ’global_def.inp’. When a component, i.e. the stringer in the prismatic section, is called in a loop, it is possible to vary the number of stringers. An example of the ”subroutine” ’prismatic_section.inp’ can be seen in appendix A.

5.1 Geometry and topology

A FEM model of the configuration with 3 stiffeners in the prismatic section and 2 stiffeners in the tapered section is shown in figure 6. Only half the structure has been modelled, because both structure and loadings are symmetric. All elements in the FEM model are four-noded Stanley type shell elements. The theory of these elements is described in reference 5.

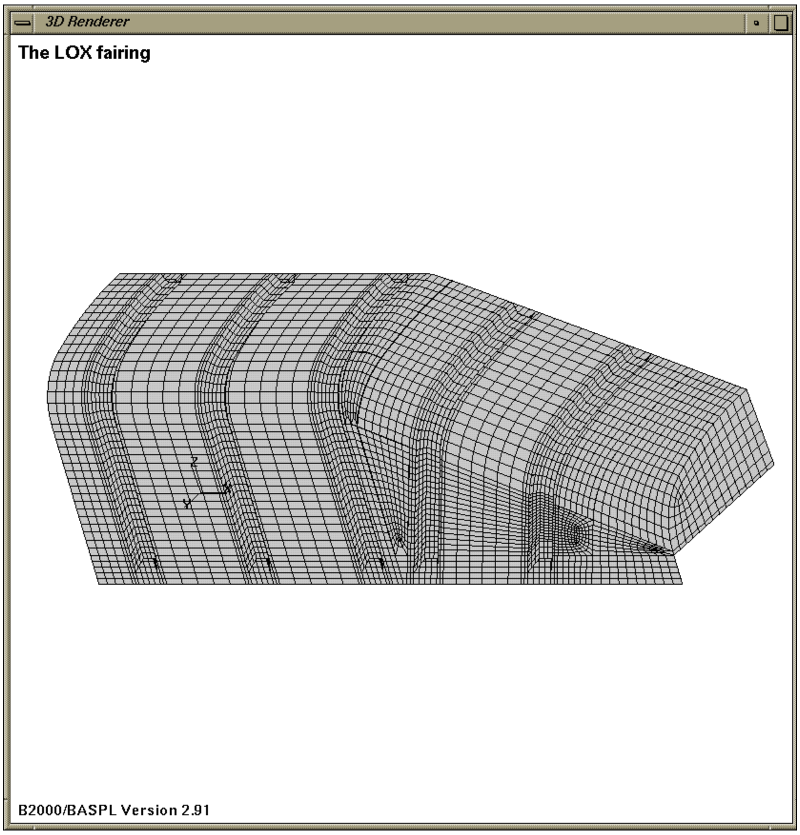

Fig. 6 The FEM model of the composite upper LOX fairing (3-2 configuration)

5.2 Materials

The material properties of the CFRP plies used in the analysis model are estimated properties. B-basis allowables will be obtained in a test programme according to ASTM STP 460 (Ref. 6), which will be completed in the beginning of 2001. Once these allowables become available, they will be used in a new set of optimisations and analyses of the LOX fairing.

All shell elements are modelled as laminates. Some of these elements have to be given an offset (e.g. the skin beneath the stiffeners). This has been done using ’air plies’, see figure 7 and reference 3. Air plies are plies with a thickness, but without any significant elastic properties or mass. The thickness of the air plies shifts the effective center line. This enables for example the shifting of the nodal grid lines, preserving a correct representation of properties leading to correct secondary bending moments.

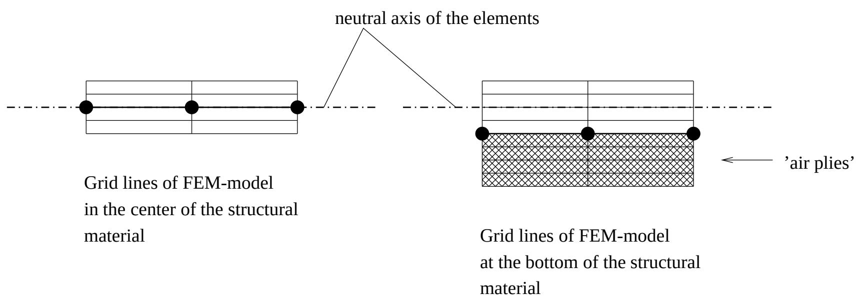

Fig. 7 The usage of air plies in the FEM-model

As said before, for the calculation of the eigenfrequency of the structure the mass of the thermal protection has to be taken into account while the stiffness properties can be neglected. Again plies with a thickness and without any significant elastic properties are added to the laminates. Only this time the plies have mass properties equal to the mass properties of the thermal protection.

5.3 Loading on the LOX fairing

The different load cases are described in chapter 2. Blast wave, acoustic and aerodynamic loads were converted by FS to static pressure loads. These pressure loads have been applied on the elements in the skin as element loads. The non-linear pressure load in the front of the prismatic section has been converted to a constant pressure load for each element using linear interpolation. The magnitude of the pressure load depends on the x-coordinates of the corners of the elements. The B2000 input processor (’b2ip’) converts the element loads to nodal forces.

5.4 Boundary conditions

Along the edges the fairing is bolted to the main stage engine thrust frame. The bolted connection is assumed to give simple support to the edges of the fairing. The support rig in the tapered section only carries radial and tangential loads.

As both the structure and the loading on the LOX fairing are symmetric, only half the fairing has been modelled and, for the calculation of stresses in the fairing, symmetric boundary conditions have been applied to the nodes in the symmetry plane. For the determination of the eigenfrequency and buckling load of the structure, calculations have been done both with symmetric boundary conditions and with anti-symmetric boundary conditions, to find the mode with the lowest eigenfrequency or buckling load, which can be symmetric or anti-symmetric.

6 The optimisation model

An analysis model describes the FEM modelling of the structure in terms of nodes, elements, materials, boundaries and loads. An optimization model describes which (material/geometric) properties may vary, which conditions should be met and how the search for better designs is controlled. The description is done manually, using the advanced ”Optimization Model Input Description Language” (OMIDL) of the B2000 code (Ref. 2). The same kind of structuring of the input decks is used as for the analysis model: a ”main programme” called ’LOX.opt’ (shown in appendix B) controls the input and calls ”subroutines”.

The changes in design are represented by design variables, like the thickness of the longitudinal plies in the skin. In order to link these variables to the plies of individual elements the so-called linking matrix is used. The optimization is subject to allowable stress levels, allowable buckling loads, a minimum eigenfrequency and geometric constraints.

6.1 Design variables

The final lay-up of the structure is determined by the optimisation. Therefore the following thicknesses have been defined as design variables:

1. Ply thickness of the longitudinal plies in the skin.
2. Ply thickness of the angle plies in the stiffeners.
3. Ply thickness of the longitudinal plies in the top of the stiffeners.
4. Ply thickness of the extra angle plies in the end of the stiffeners.
5. Ply thickness of longitudinal plies in the flat rear part of the fairing.

Further, two geometrical variables have been defined:

6. Width of the stiffeners.
7. Height of the stiffeners.

The angle of the sides of the stiffener with respect to the skin remains constant (60^o), so when the top of the stiffener becomes wider, naturally the base becomes wider as well. Notice that the base also becomes wider, when the stiffener becomes higher.

6.2 Design variable Linking

Here a short description of the linking of design variables to FEM details is given. The theoretical background can be found in reference 1.

The principle of design variable linking is simple: the linking matrix reflects the linear combination of changes in design variables, which results in the change of model details.

$$\left\{MP^i_{new} - MP^i_{old}\right\} = [C_{ij}] \cdot \left\{x^j_{new} - x^j_{old}\right\}$$

In this relation MP stands for Model Parameter, x is the Design Variable (DV) and $[C_{ij}]$ is the linking matrix.

For example, Design Variable 6 is called 'width of the stiffeners'. When DV 6 increases, this has to result in a new model with wider stiffeners. The x-coordinates of the nodes in the stiffeners will have to be adapted. The x-coordinate of each node is a Model Parameter and the magnitude of the change is defined in the linking matrix. Notice that when the stiffeners become wider, the skin has to become narrower, so DV 6 is not only linked to the nodal coordinates of the stiffeners, but to the nodal coordinates of the skin as well.

6.3 Constraints

Constraints on the design are stress constraints, buckling constraints and eigenfrequency constraints in case "light loads" are applied. They have been deducted from the design requirements (chapter 3). As stress failure criterion the Tsai-Hill criterion is used. Each ply in each element has to satisfy the Tsai-Hill criterion, but only the outer plies within an element have to be checked.

Global buckling is not allowed below Design Ultimate Load. Local buckling is not allowed below Design Limit Load. The buckling constraint proved to be not an active constraint during the optimisation. Therefore, only a final check whether this constraint is satisfied, is reported, which saved lots of computing effort during the optimisation.

”Light loads” instead of ”heavy loads” may be applied to the LOX fairing when the eigenfrequency is higher than $176.8Hz$. This results in two separate optimisations:

1. Use ”heavy loads” for calculation of stresses, do not apply constraint on eigenfrequency.
2. Use ”light loads” for calculation of stresses, apply constraint on eigenfrequency.

The constraint is imposed on the first four eigenmodes of the structure when the ”light loads” are applied.

Another type of constraint within B2000 is the objective itself. The objective is the structural mass of the entire LOX fairing, because the total costs are strongly related to the mass.

7 Optimisation procedure

Several configurations of the fairing were analysed and optimised, first with the heavy loads and then with the light loads in combination with the eigenfrequency constraint. To achieve a fully optimised design the following optimisation process has been used:

1. build analysis model with initial geometry and thicknesses (’b2ip’)
2. build optimisation model with initial geometry and thicknesses (’b2omip’)
3. run optimisation (’b2opt’) with a maximum of 6 Maxi-cycles
4. Convergence?
   - No: return to 1. using the results of the optimisation for the initial geometry and thicknesses
   - Yes: stop

This method has been used because of the following. The structure is in a state of static equilibrium:

$$K \cdot U = P$$

The optimisation uses the derivative with respect to the Design Variable of this equation to calculate the displacement/stress gradients:

$$K_{,x} \cdot U + K \cdot U_{,x} = P_{,x}$$

Usually the right hand term can be neglected ($P_{,x} = 0$). However, this is not allowed here. As said before, the pressure distribution is converted to nodal loads by the input processor. The change of geometry causes a non-uniform pressure distribution on the LOX fairing (illustrated in figure 8), which in reality is not the case. In other words, the nodal forces depend on the geometrical variables (stiffener width and height) and therefore $P_{,x} \neq 0$. Figure 9 shows the influence of the neglection of $P_{,x}$ on the optimisation for the configuration with 3 stiffeners in the

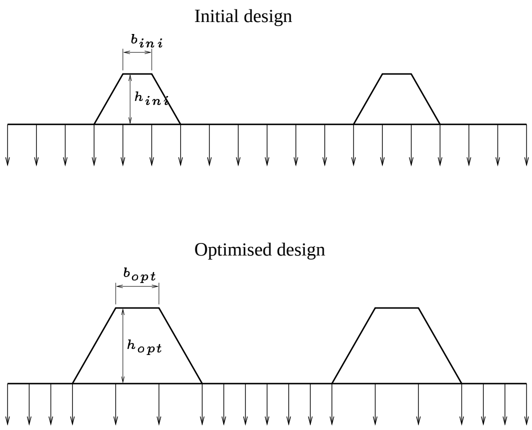

Fig. 8 The nodal loads due to the internal overpressure on the LOX fairing (before and after optimisation)

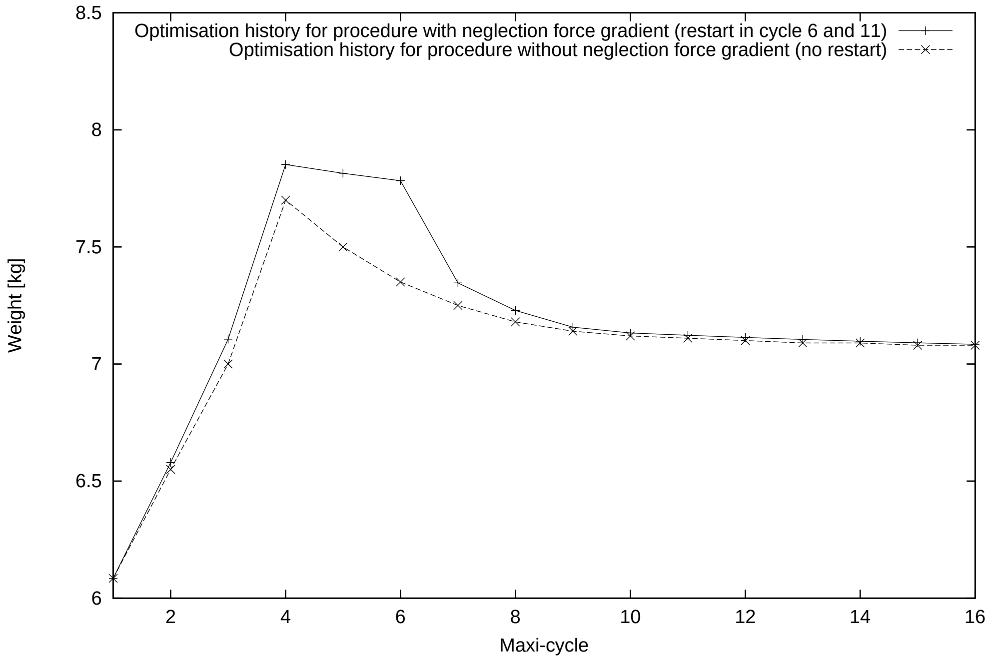

Fig. 9 The optimisation history with/without neglection of the force gradient $P_{,x}$ for the 3-2 configuration. The curve without neglection of the force gradient is an expectation, the procedure is not operational yet

prismatic section and 2 stiffeners in the tapered section. In Maxi-cycle 5 and 6 the decline of the objective is only very small and the optimisation has almost achieved convergence, but the new optimisation with a redistribution of the nodal forces shows a much stronger decline of the objective (Maxi-cycles 7, 8, and 9). If the optimisation would not have been restarted, the nodal forces would not have been redistributed and the wrong optimum would have been found. Of course there are other ways to solve this problem. The change of nodal forces could be solved by linking the geometrical design variables to the nodal forces, but ideally this problem would be solved by the optimisation itself. This feature will be programmed into the development code (in the input processor 'opip'), but it is not fully operational yet. In figure 9 the optimisation is shown as is expected for the procedure taking into account the force gradient $P_{,x}$.

8 Optimisation results

Several fairing configurations have been optimised. The results showed that the configuration with 4 stiffeners in the prismatic section and 3 stiffeners in the tapered section has the lowest weight. The optimisation results of this configuration will be discussed here in greater detail.

The history results of the optimisation can be seen in figures 10 to 17. The optimisation with the heavy loads started with an initial design that was already close to the optimised design. As starting point for the optimisations with the light loads and the extra constraint on the eigenfrequency, the previously optimised design (for the heavy loads) was used. It can be seen that the results of both optimisations (heavy loads/light loads) for this configuration do not differ much. The stresses in the structure can be seen in figures 18 and 21. Stresses are lower throughout a great part of the fairing for the design optimised with the light loads.

The eigenfrequency of the design, optimised with the light loads and with the extra constraint on the eigenfrequency, ends up being close to the critical eigenfrequency. The eigenfrequency of (and therefore the loads on) this design will be sensitive to changes in thermal protection mass; a

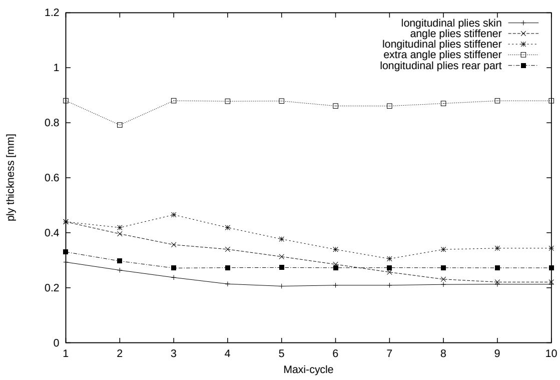

Fig. 10 Ply thicknesses during the optimisation (heavy loads) for the 4-3 configuration

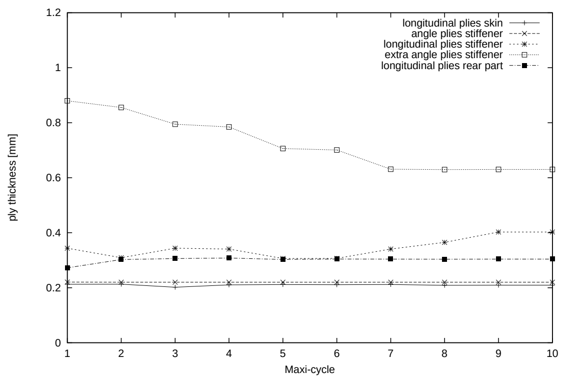

Fig. 11 Ply thicknesses during the optimisation (light loads) for the 4-3 configuration

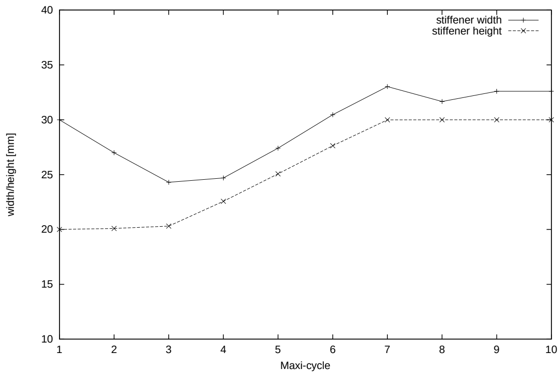

Fig. 12 Stiffener width/height during the optimisation (heavy loads) for the 4-3 configuration

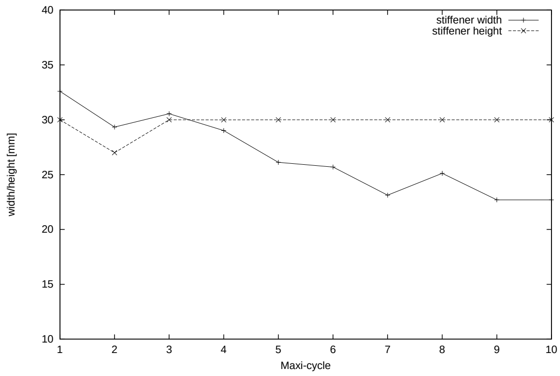

Fig. 13 Stiffener width/height during the optimisation (light loads) for the 4-3 configuration

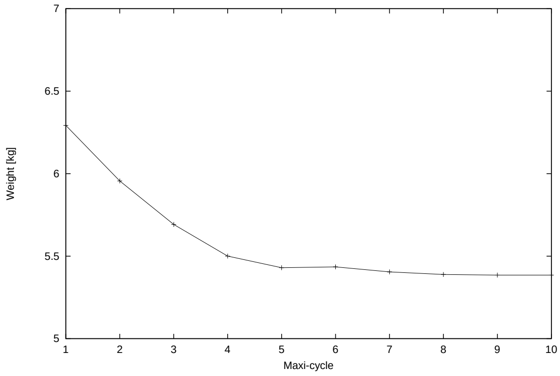

Fig. 14 The weight of the fairing during the optimisation (heavy loads) for the 4-3 configuration

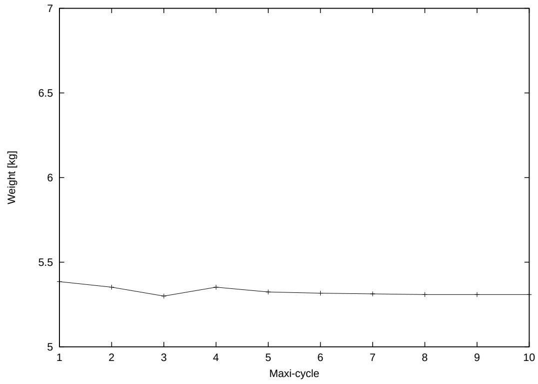

Fig. 15 The weight of the fairing during the optimisation (light loads) for the 4-3 configuration

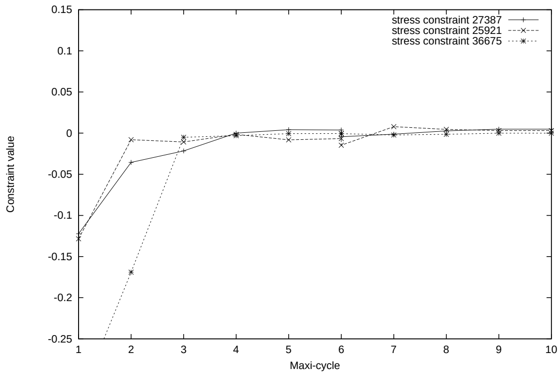

Fig. 16 Constraint values during the optimisation (heavy loads) for the 4-3 configuration

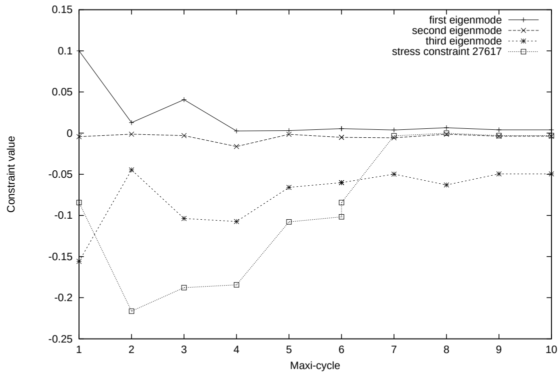

Fig. 17 Constraint values during the optimisation (light loads) for the 4-3 configuration

higher mass of the thermal protection will lead to a lower eigenfrequency and could possibly lead to failure of the structure, while (for this particular configuration) only a very small weight reduction is offered by this design compared to the design optimised with the heavy loads. Therefore it was decided to use the design, which was optimised with the heavy loads, in the further development of the demonstrator fairing. All ply thicknesses of this optimised design were translated/rounded up to a discrete number of plies. On this design a stress analysis has been performed (not shown here). Further, the first two eigenfrequency modes and buckling modes of this design can be seen in figures 22 to 25. Finally, the composite LOX fairing offers a structural weight reduction of almost 50% compared to the current metallic fairing.

9 Conclusions

Several fairing configurations, each with a different number of stiffeners, have been analysed and optimised with the Finite Element code B2000. By using the ”Input Description Language” and the ”Optimisation Model Input Description Language” the model has been almost completely parametrised and this enabled the quick changes of number of (hat-)stiffeners, lay-up, mesh density, etc.

On each configuration two separate optimisations have been performed. In one optimisation heavier loads were applied with stress constraints. In the other optimisation lower loads were applied with the same stress constraints and with an additional constraint on the eigenfrequency. The fairing configuration with four stiffeners in the prismatic section and three stiffeners in the tapered section resulted in the design with the lowest weight. The eigenfrequency of the ”light load” design ended up being close to the critical eigenfrequency. The eigenfrequency of (and therefore the loads on) the fairing would be sensitive to changes in thermal protection mass. A higher mass of the thermal protection would lead to a lower eigenfrequency (with heavy loads) and could possibly lead to failure of the structure, while (for this particular configuration) only a very small weight reduction is offered by this design compared to the design optimised with the heavy loads. Therefore it was decided to use the design, which was optimised with the heavy loads, in the further development of the LOX fairing (translation of ply thicknesses to discrete number of plies, buckling analyses, etc.).

Initial calculations (involving the amount of material, labour, etc.) showed that the aim of a 50% reduction of the recurring costs will be achieved. In addition, the composite LOX fairing offers a structural weight reduction of almost 50% compared to the current metallic fairing. The composite LOX fairing design is the result of analyses and optimisations with estimated material properties. B-basis allowables will become available from a test programme, which will be completed in the beginning of 2001. The B-basis allowables will be used in a new set of optimisations and analyses, resulting in a final design. This design which will be further detailed and analysed (e.g. connections) and these activities will result in the issue of production drawings of a mould and of a full scale fairing demonstrator in the year 2001.

10 References

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3. Arendsen, P.; *Optimization Study of the Window Area for an Ultra High Capacity Aircraft*, NLR-TR-98422, National Aerospace Laboratory NLR, Amsterdam, 1998.
4. Merazzi, S.; *B2000 Input Description Language (IDL)*, SMR Corp., Bienne, Switzerland, 1995.
5. Stanley, G.M.; *Continuum Based Shell Elements*, Lockheed Applied Mechanics Laboratory, 1985.
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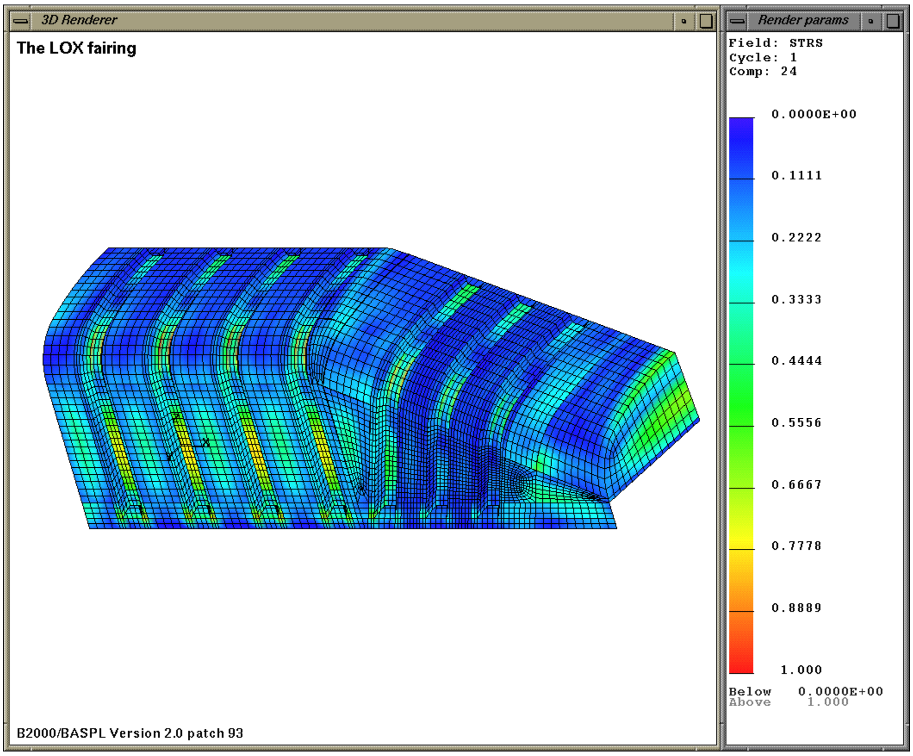

Fig. 18 The Tsai-Hill criterion (heavy loads) in the elements of the LOX fairing (initial design)

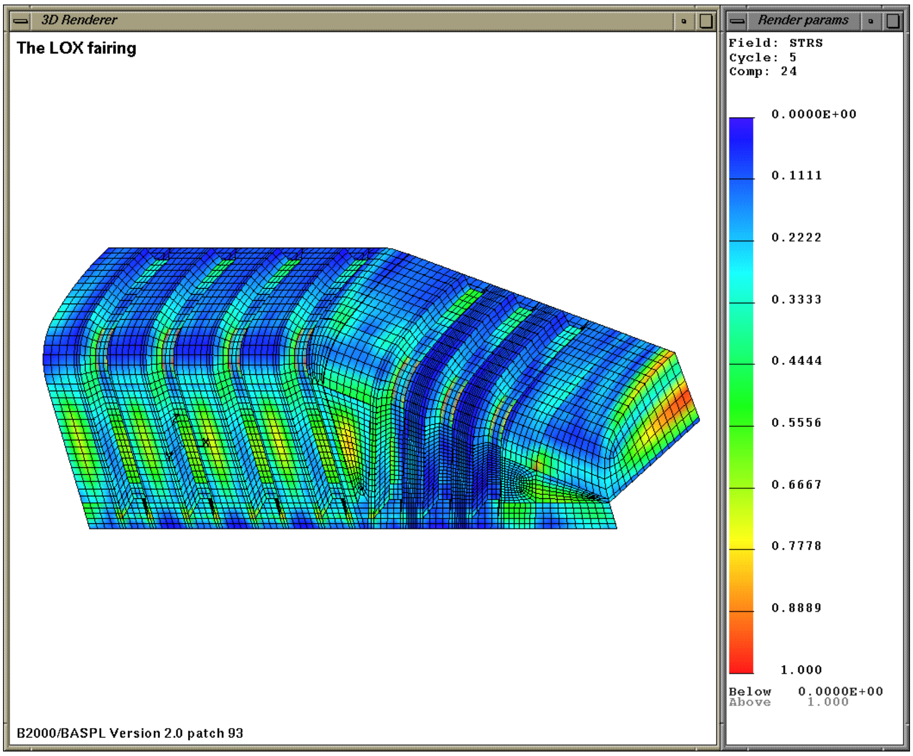

Fig. 19 The Tsai-Hill criterion (heavy loads) in the elements of the LOX fairing (optimised design)

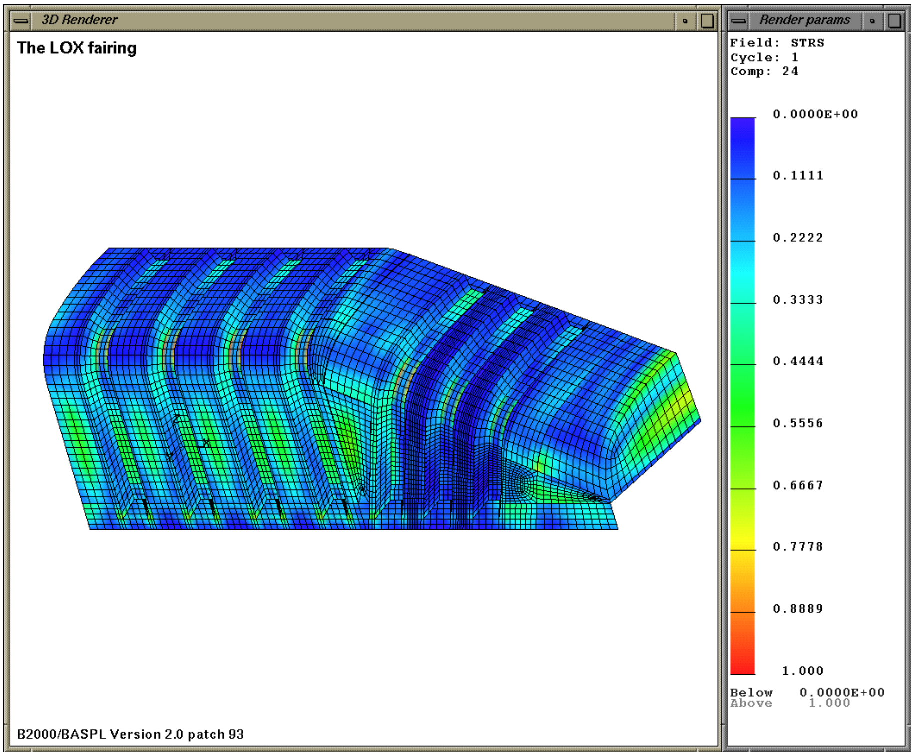

Fig. 20 The Tsai-Hill criterion (light loads) in the elements of the LOX fairing (initial design)

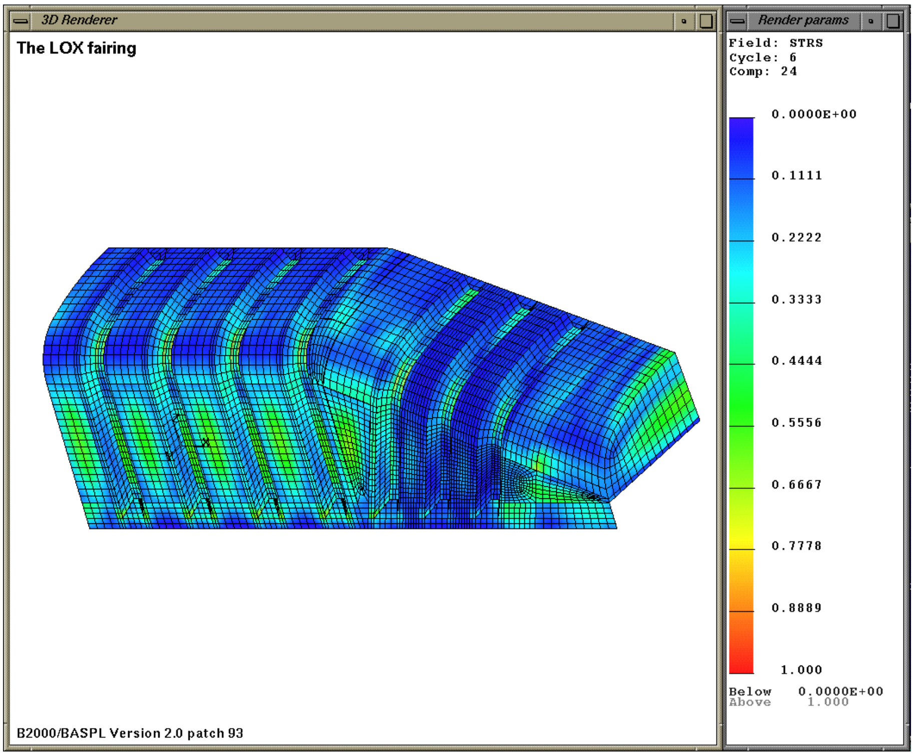

Fig. 21 The Tsai-Hill criterion (light loads) in the elements of the LOX fairing (optimised design)

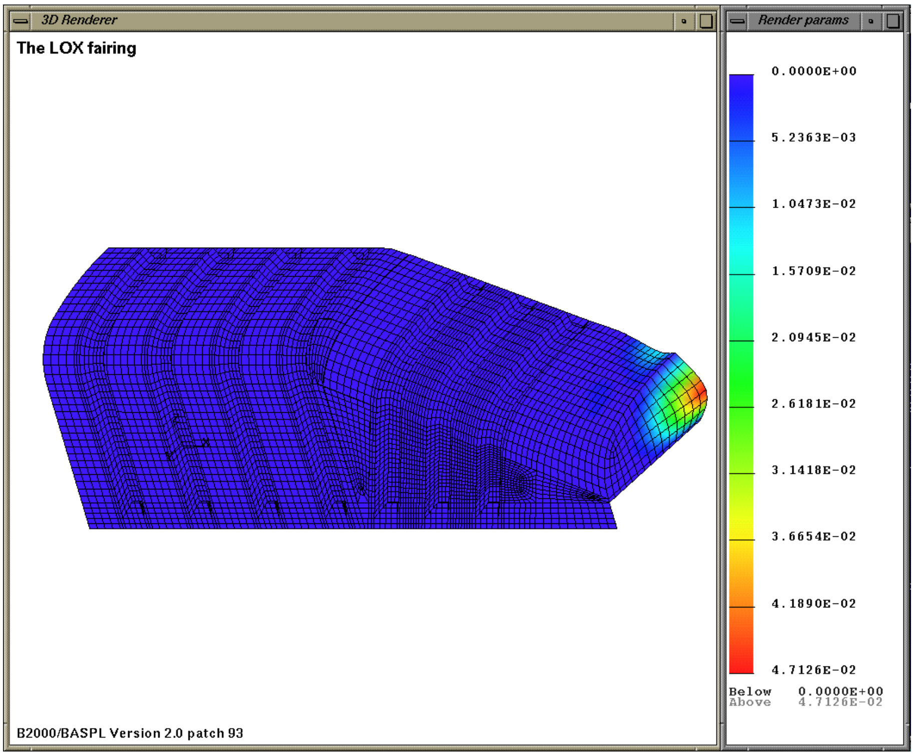

Fig. 22 The first eigenmode of the final design, $f_n = 173Hz$

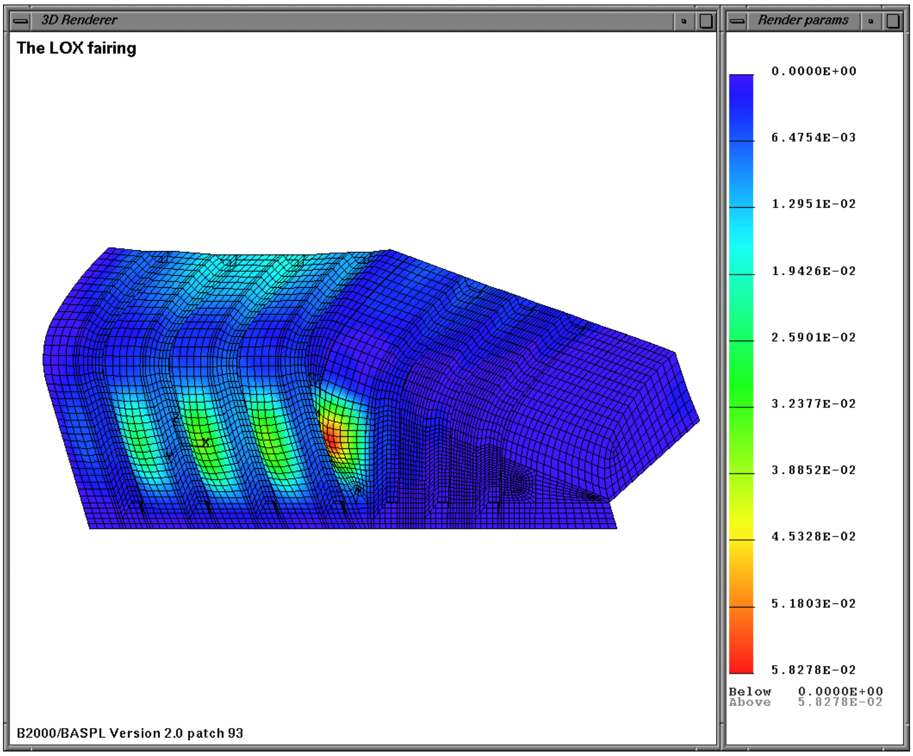

Fig. 23 The second eigenmode of the final design, $f_n = 190Hz$

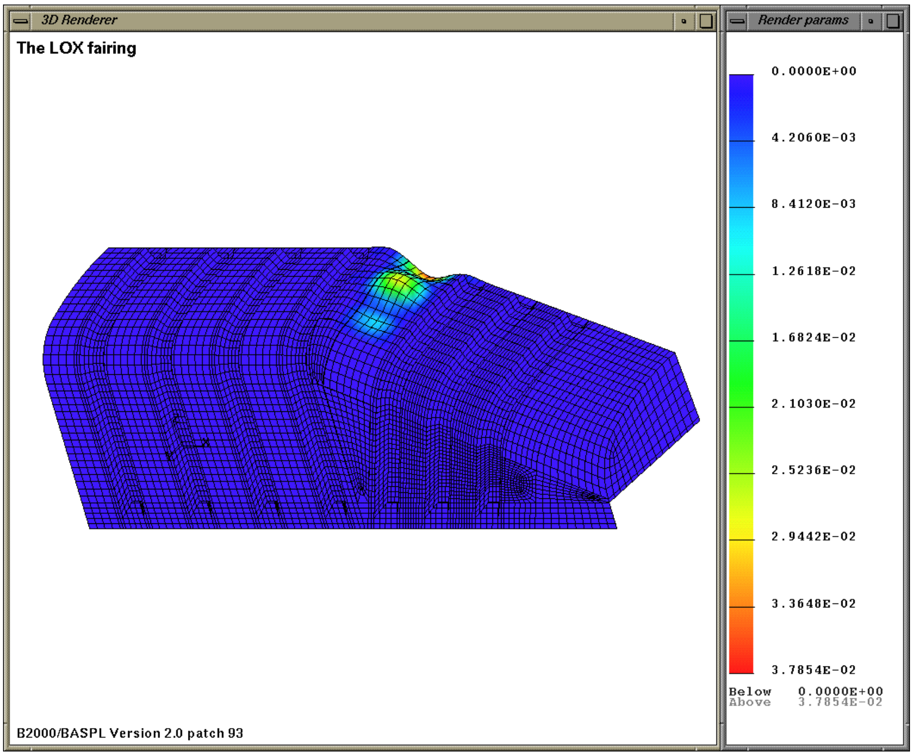

Fig. 24 The first buckling mode of the final design, $\lambda = 1.23 \cdot$ Limit Load

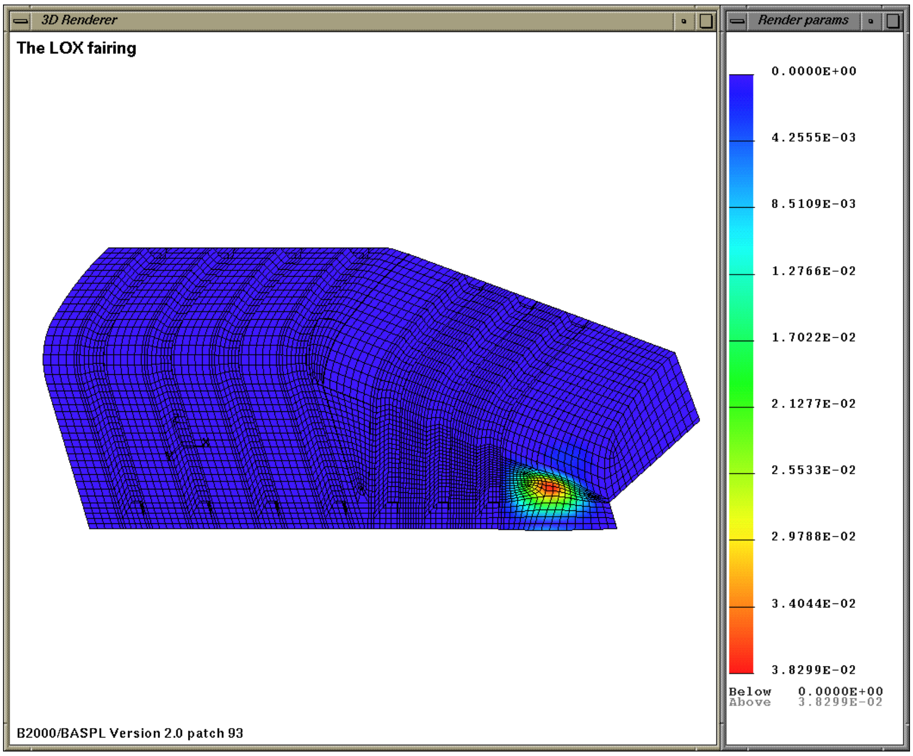

Fig. 25 The second buckling mode of the final design, $\lambda = 1.35 \cdot$ Limit Load

Appendix A B2000 analysis model input deck, 'prismatic_section.inp'

```
(phi1_psr=(phi1_ps*pi/180));
(phi2_psr=(phi2_ps*pi/180));
(chi_psr=(chi_ps*pi/180));
(phi_str=(phi_st*pi/180));

#skin form x0 to first stringer
(x=(x0_ps));
(width=(x1_ps-(s_ft_ps+s_st_ps/2+h_st_ps/tan(phi_str))-x0_ps));
(nnx=(nnsk1_ps));
(ibound=1);
@skin_ps.inp;

#first stringer
(x_st=(x1_ps));
(ibound=2);
@stringer_ps.inp;

#second, third, n'th stringer + skin between stringers
(k=1);
if (n_str_ps>1) (
   (x_strpch=((xn_ps-x1_ps)/(n_str_ps-1)));
);
while ( k<(n_str_ps) ) (

      (k=(k+1));

      (x=(x_st+s_ft_ps+s_st_ps/2+h_st_ps/tan(phi_str)));
      (width=(x_strpch-(2*s_ft_ps+s_st_ps+2*h_st_ps/tan(phi_str))));
      (nnx=(nnski_ps));
      (ibound=2);
      @skin_ps.inp;

      (x_st=(x_st+x_strpch));
      (ibound=2);
      @stringer_ps.inp;
);

#skin form n'th stringer to x=L_psts
(x=(x_st+s_ft_ps+s_st_ps/2+h_st_ps/tan(phi_str)));
(width=(L_psts-x));
(nnx=(nnskn_ps));
(ibound=2);
@skinn_ps.inp;
```

Appendix B B2000 optimisation model input deck, ’LOX.opt’

```
#***************************************************************************
# This is the Optimization Model Input file for the B2000 FE-optimizations
# on the Lower Drag Brace Design. It consists of an intuative input
# language (IDL), with which the entire model is created in parametrized form
#
# This input file ’calls subroutines’ ie. other input files for modelling
# specific parts. There are the following ’subroutines’:
#
# global_def            ; consists out of all user defined parameters which
#                         make up the entire structure
# cons_weight ; Defines the total weight of the structure (Obj.)
#
#***************************************************************************

#***************************************************************************
# Global definitions
#
@global_def.inp


#***************************************************************************
# Start input deck: Design variable definition
#
DESV
   MI=0.9 MA=1.1111
   SCORDV=1.0
#  idv  name              xlb             xanal            xinit           xub
#   (xlb=0.050); (xub=10.00);
#    1   T_angle_skin     (xlb)       (tply_ask*1.e3)     (0.220)         (xub)

   (xlb=0.050); (xub=0.2933);
    2   T_longi_skin     (xlb)        (tply_lsk*1.e3)     (0.257)         (xub)

   (xlb=0.220); (xub=10.00);
    3   T_angle_stif     (xlb)        (tply_ast*1.e3)     (0.270)         (xub)

   (xlb=0.050); (xub=10.00);
    4   T_longi_stif     (xlb)        (tply_lst*1.e3)     (0.550)         (xub)

   (xlb=(tply_aov*1.e3)); (xub=((tply_aov+3*tply)*1.e3));
    5   T_angle_over     (xlb)        (tply_aov*1.e3)      (xub)          (xub)

#   (xlb=0.220); (xub=0.220);
#    6   T_longi_over     (xlb)        (tply_lov*1.e3)     (0.220)         (xub)

   (xlb=0.050); (xub=10.00);
    7   T_longi_rear     (xlb)        (tply_rea*1.e3)     (0.260)         (xub)
```

```
   (xlb=20.00); (xub=50.00);
    8   Stiffener_width (xlb)        (s_st_ps*1.e3)      (s_st_ps*1.e3)    (xub)

   (xlb=20.00); (xub=30.00);
    9   Stiffener_height (xlb)       (h_st_ps*1.e3)      (h_st_ps*1.e3)    (xub)

END

#*****************************************************************************
# Design variable linking
LINK
  MODEL=1;
  AMP=TH;
#    IDV=1 (coeff=1.0e-3); @link_t_angle_skin.opt;
    IDV=2 (coeff=1.0e-3); @link_t_longi_skin.opt;
    IDV=3 (coeff=1.0e-3); @link_t_angle_stif.opt;
    IDV=4 (coeff=1.0e-3); @link_t_longi_stif.opt;
    IDV=5 (coeff=1.0e-3); @link_t_angle_over.opt;
#    IDV=6 (coeff=1.0e-3); @link_t_longi_over.opt;
    IDV=7 (coeff=1.0e-3); @link_t_longi_rear.opt;
  INDEX=1;
    IDV=8 (coeff=1.0e-3); @link_stfwdth.opt;
    IDV=9 (coeff=1.0e-3); @link_stfhght.opt;
  ENDMODEL
END

#*****************************************************************************
# Constraint definition
CONS
# Total Mass (Objective)
    (coeff=one); lo=(zero); up=(large); index=0
  CID=1; METH=1;  CTYPE=mass name=total_weight;   @cons_weight.opt;

  SINGLE=ON;

#  cid=11; ctype=freq; name=eigen_frequency_mode_1; meth=1
#     (coeff=(one)); lo=176.8; up=(large); coef=(coeff); 1
#
#  cid=12; ctype=freq; name=eigen_frequency_mode_2; meth=1
#     (coeff=(one)); lo=176.8; up=(large); coef=(coeff); 2
#
#  cid=13; ctype=freq; name=eigen_frequency_mode_3; meth=1
#     (coeff=(one)); lo=176.8; up=(large); coef=(coeff); 3
#
#  cid=14; ctype=freq; name=eigen_frequency_mode_4; meth=1
#     (coeff=(one)); lo=176.8; up=(large); coef=(coeff); 4

  cid=401;  meth=4; ctype=buck; name=buckling;
     (coeff=one); case=4   ; lo=(-0.1);     up=(0.8);    coef=(coeff) 1 2 3 4;
```

```
# Stress constraints
# cmp=17        => Tsai-Hill/ Von Mises
# cmp=13,14,15  => Principal stresses (sorted in ascending order)
# cmp=25        => Maximum shear stress max[ (P1-P2)/2 , (P1-P3)/2 , (P2-P3)/2 ]
#
  SCORCN=-1.0;
  cid=1001; meth=+3; ctype=sigm; name=stress;
     cmp=17; (coeff=one); case=1; lo=(-(large));   up=(one);   @cons_stress.opt;

END

#****************************************************************************
# Optimization control
OPTC
  OBJ=1;
  MAXCYC=6; REPS=1.0E-6; EPS=1.0E-6;
  CVM=4; HTRESS=-0.1; FTRESS=-0.3; IAL=2;
END

RUN
```