Preliminary Structural Analysis of a Thermal Deflector of Carbon Fiber and Cork Sandwich for Space Applications

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Abstract

In a demanding industry such as space industry the weight reduction of the components is a priority.
In this thesis it is intended to perform the design and the preliminary structural analysis of a thermal deflector of an apogee boost motor (ABM), proposing an alternative to the current stainless steel deflectors.
The main goal of this project is to prove the mechanical robustness of cork for a non-ablative space application, through the utilization of carbon fibers and cork sandwich composites.
Two thermal deflectors made of carbon fiber and cork sandwich composites were studied. Both deflectors had cork agglomerate as core material, but two options were proposed for the skins: Carbon Fiber Reinforced Polymer (CFRP) and carbon fiber reinforced carbon matrix (C/C composite).
The requirements and the mechanical environment, that this deflector will withstand, were defined and an optimization of the sandwich was performed subjected to these constraints.
Based on the results of static and dynamic analyses, it is possible to conclude that both deflectors will survive to all the loads applied at the mechanical interface, with a weight reduction in the order of 76% when compared with the current deflectors.
The present research shows the potential for the development of new space applications with carbon fibers-cork sandwich composites in a near future.
Keywords: Thermal Deflector, Sandwich Composites, Carbon Fibers, Cork, Finite Element Analysis

1. Introduction

1.1. Objective

The main goal of this project is to prove the mechanical robustness of cork for a non-ablative space application, through the utilization of carbon-cork sandwich composites. To achieve this target, design and preliminary structural analysis of a thermal deflector of an apogee boost motor (ABM) will be performed.
This work presents a structured and complete approach to design and analyse a spacial component.
It is expected in a short term period to open new opportunities in space industry for cork applications.

1.2. Context of the Project

This project, funded by the European Space Agency (ESA), was developed during a six months internship within Active Space Technologies (AST) and in partnership with Amorim Cork Composites (ACC).
This work will contribute to expand AST's knowledge of composite materials, and push the Portuguese economy forward, through the application of cork (national product) for a new space application.

1.3. Motivation

In a demanding industry such as space industry the mass reduction of the components is a priority to reduce costs. Since the massification of composite materials, several new lightweight applications were proposed and manufactured. It is estimated that the current thermal deflectors (made of stainless steel) weight in the order of 6kg. Through the application of carbon-cork sandwich composites a reduction of weight of an order of three times is a possible target. Because of this major weight reduction is extremely important to verify the mechanical behaviour and the structural integrity of a thermal deflector made of these materials.

1.4. State of The Art

Cork is a natural, renewable and sustainable material. This material presents remarkable properties when introduced as a core of a sandwich structure. The main properties are the high damage tolerance to impact loads, good thermal and acoustic insulation and excellent damping characteristics [1] [2]. For these reasons, cork is a subject of great interest and the scientific literature is vast. A review of cork properties, capabilities and applications was published in 2008 by Silva et al [3].

1.4.1 Cork Composites

It was noted that, since the industrialization of cork, to manufacture cork stopper it generates a large amount of waste material. For this reason, was needed to find a way of avoid this issue, and one of the solutions to fulfil this need was the development of composite materials containing cork. The material resultant from this process is called cork-based agglomerate. There are two types of cork agglomerates: white agglomerates, composed by cork granules bonded by an adhesive product and the black agglomerates, made by cork granules exclusively where the self-agglomeration of the granules occurs due to the compression and heating [2].

Allying the cork properties with the technological development of sandwich composites it is possible to consider it as a viable alternative to other low weight core materials used in aerospace structures, such as polymeric foam cores [1].

In the transport industry, the demand for lightweight structures with an high strength to weight ratio unlocked several opportunities for cork applications, since the desired properties for a core material are coincident with cork's properties.

To sum up, the cork-based agglomerates answers effectively to technical and environmental goals that constitute the paradigm of transport in the future.

1.4.2 Cork Space Applications

Cork have been extensively applied in the space industry. The main application of cork is for thermal protection system (TPS), through ablative solutions, which consist in the erosion of the material to dissipate energy. The ablative solutions are used for the atmospheric re-entry. Efforts to develop cork new space applications, including non-ablative TPS, are being done by the European Space Agency.

One of the cork space applications is the Atmospheric Reentry Demonstrator, described bellow.

1.4.3 Atmospheric Reentry Demonstrator

This mission was the ESA's first Earth return craft. In 1998, for the first time Europe flew a complete space mission, and it was possible to launch a vehicle into space and recovering it safely [4]. It is possible to see on Fig. 1 that the cone section is made of a material named Norcoat which is composed mainly of cork powder and phenolic resin . This material is one of the thermal protection systems (TPS) used in this mission [5].

Figure 1: Main figure: ARD before flight mission. Inset: ARD post-flight figure [4]

After the proven success of this material, it was also applied on Beagle 2 (2003) and Netlander (2007) and will be used on Exomars mission in 2016 [6].

2. Thermal Deflector Design

The thermal deflector is intended to be integrated on Spacebus 4000 (Fig. 2), which is a medium-class telecommunication geostationary satellite bus made by Thales Alenia Space (TAS) and is designed to be launched by Ariane 5 launch vehicle.

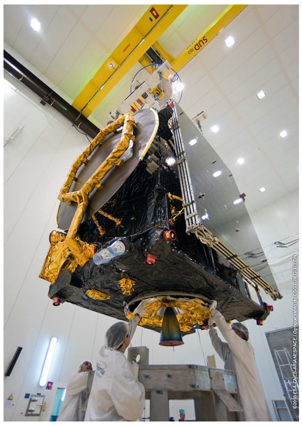


Figure 2: Thermal Deflector integrated on Spacebus 4000 at the base of Apogee Boost Motor (Source: ESA)

The main purposes of the thermal deflector are:

- Provide structural support to multi-layer insulation
- Serve as thermal radiation shield to separate payload cold areas from high temperature thruster
- Upgrade the thermal insulation of the spacecraft with respect to the apogee boost engine firing phase

Fire resistant studies leverage the use of cork for this specific application.

The thermal deflector only has a mechanical interface between the spacecraft.

2.1. Definition of Requirements

This project will consist in analyse two carbon-cork sandwich structures; NL25 cork agglomerate as core material, but two options were proposed for the skins: Carbon Fiber Reinforced Polymer (CFRP) and carbon fiber reinforced carbon matrix (C/C composite).

2.1.1 Geometrical Requirements

The final assembly is presented as a truncated cone partially closed at the top side by a disk.

2.1.2 Interface Requirements

For integration purposes, the thermal deflector shall be divided in 4 identical sub-parts, otherwise it would not be possible to install the deflector after the thruster. The mounting of this parts on the spacecraft shall be located at the cone edges and no mounting device shall exist in the disk area. The integration shall be reversible (e.g. bolted). This way it is also easier to modify the deflector without interfering with other systems.

2.1.3 Structural Requirements

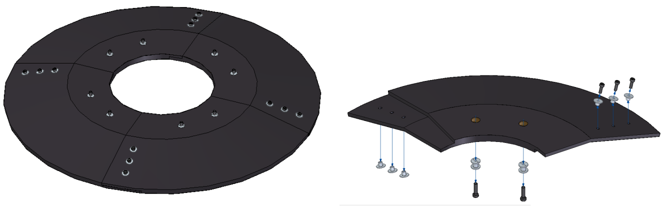
In a static environment the system shall survive to a 30G acceleration on all directions, simultaneously.

In a forced vibration environment the system shall survive when loads of 11.8 gRMS at the mechanical interfaces are applied. In the 200 mm to 360 mm diameter plane the displacement under the previous mentioned mechanical loads should be less than 2 mm on the plane and less than 5 mm out of the plane.

Although end-user did not quantified, the mass and the overall thickness shall be as low as possible.

2.2. Concept Design

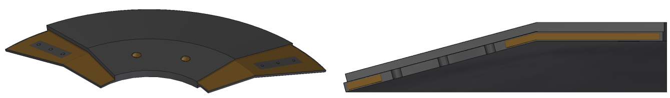
The designed thermal deflector can be seen on Fig. 3.



(a) Thermal Deflector full assembly (b) Quarter exploded view

Figure 3: Thermal Deflector detailed CAD design

The interface with spacecraft is done with M5 bolts, spaced, in each quarter, 30 degrees between them. Inserts on this area are needed to provide tightening stiffness. The joints between the quarters are performed in the conical surface, as requested, through the utilization of three M4 bolts. To lock this bolts are introduced in this region six sleeves, three of them threaded. To reinforce this region, a block is introduced to cover the holes, as can be seen on Fig. 4. To view this zone, an angular cut was done through the middle of thickness (left) and a radial cut (right).



(a) Angular cut (b) Radial cut

Figure 4: Block reinforcement close the M4 bolts

3. Finite Element Model

The finite element analysis' software used was MSC Nastran$^{\text{TM}}$2013 and the pre and post-processing performed with the Patran$^{\text{TM}}$2013.

3.1. Thermal Deflector Geometry

To have mesh control and follow the element sizes carefully, it was needed to discretizate the geometry. The criteria was to separate material discontinuities, and geometric differences, as the case of the 5 mm diameter holes Fig. 5.

3.2. Material Properties

It is intended to design two thermal deflectors with different sandwich composites. The common element is the core of the sandwich, which is cork NL25, provided by ACC, and its properties can be seen on Table 1. One of the deflectors is made of carbon fiber reinforced polymer, with 60% fiber volume ratio, and its properties were extracted by AST, based on experimental results obtained from a previous project [7] [8].

The other thermal deflector is made of carbon fiber reinforced carbon matrix, and the properties of this material, with a fiber volume ratio of 40%, were obtained by Cambridge Engineering Selector (CES) software and can be seen on Table 3. Both, carbon-carbon composite and the core cork, will be considered isotropic materials. The reason to approach the behaviour of cork as isotropic is the fact of this material absorbs a small percentage of resin, which alters its natural properties (Table 1). The CFRP will be considered an orthotropic material Table 2.

Table 1: Cork NL25 properties

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Table 2: CFRP properties

Young Modulus 11 (GPa)	142,9	Tension Strength 11 (GPa)	2,28
Young Modulus 22 (GPa)	3,4	Tension Strength 22 (MPa)	57
Shear Modulus 12 (GPa)	1,21	Compression Strength 11 (GPa)	1,44
Density (kg/m^3)	1530	Compression Strength 22 (GPa)	0,23
		Shear Strength (MPa)	71

Table 3: C-C properties

Young Modulus (GPa)	79	Tensile Yield Strength (MPa)	23
Shear Modulus (GPa)	29,9	Compressive Yield Strength (GPa)	0,25
Density (kg/m^3)	1720	Shear Yield Strength (MPa)	20

3.3. Elements Properties

The elements used to model the heat shield were quadrilateral, flat plate shell elements: CQUAD4. According to [9] this type of element has two coordinate systems: the element and the material. The first coordinate system is defined in the center of the element. The second is centred in one of the element's vertex and is coincident with an external coordinate system to define the orientation of the fibers. The fibers orientation were defined through the creation of an additional coordinate system, with origin in the center of the thermal deflector, and the zero degree orientation was defined as a radial direction Fig. 5.

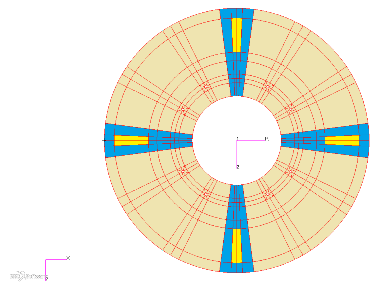

Figure 5: Material Properties Discontinuities on Thermal Deflector

Another important aspect, is the existence of properties discontinuities due to the interface presence. To clearly identify this variations table 4 provides the given name and the composition of the material in this regions. On Fig. 5 the light brown, blue and yellow are the global, interface and block properties, respectively. Although this variation of properties, the total thickness remains constant in all the thermal deflector.

Table 4: Properties presented on thermal deflector

Property Name	Composition
Global	skin + core + skin
Interface	skin + core + skin + skin + core +skin
Block	skin

3.4. Boundary Conditions

The common boundary conditions applied to the subsequent analysis were zero translational and rotational displacements on the nodes close to the 5 mm diameter holes, simulating the support interface with other structural components.

3.4.1 Modal Analysis

The reason to perform this analysis is to understand the basic dynamic behaviour of the thermal deflector when subjected to a perturbation.

To perform a modal analysis, the inputs needed are the support conditions previously mentioned.

3.4.2 Static Analysis

It was applied an inertial 30G acceleration on all axis simultaneously, to simulate, in a conservative approach, all the stages this deflector goes through.

3.4.3 Forced Vibration Analysis

To understand the behaviour of the thermal deflector under a dynamic excitation, it is needed to perform a dynamic structural analysis [10].

The objective of this section is to cover all the excitations that the deflector will withstand and accomplish the requirements defined on section 2.2.

Modes' Contribution In this section will be analysed the influence of the number of modes used to compute the solution. Since the solution (displacements) is a linear combination of the normal modes, the response will be influenced until a certain number of modes (in a frequency range). It is important to perform this analysis to ensure the results' quality and, at the same time, save computational effort.
It will be applied an acceleration of 1g in the support nodes and observed the response in a range of frequencies between 20 and 2000Hz.

Frequency Response with Damping This analysis is of major importance to understand the dynamic response of the thermal deflector above 100Hz, and will be the input for the random analysis. It will be applied 1g acceleration in a range between 100 to 2000Hz. Since the excitation vibrations applied will go through the natural frequencies of the system, it is fundamental to apply a damping coefficient to the thermal deflector. Due to the lack of experimental data, it was necessary to estimate this value. Based on [11] and [12] the total loss factor η_t of the composite material, can be approximated to the loss factor of the core. The value used for the loss factor was 0.13, which corresponds to a NL20's core. Although this approximation, it is expectable that the behaviour of a NL25 core will not be significantly different and it can be considered a reasonable first estimation.

3.4.4 Random Analysis

Random analysis can be considered as an extension of frequency response analysis. To perform this analysis is needed to define the acceleration spectral density (ASD) curve. It is applied a constant ASD between 100-500Hz range with a value of 0.1 g^2/Hz and from 500Hz until 2000Hz is reduced linearly from the previous value until 0.05 g^2/Hz Fig. 6.

The integral of the ASD curve gives the acceleration root mean square (RMS) value, which is equal to 11.8gRMS.

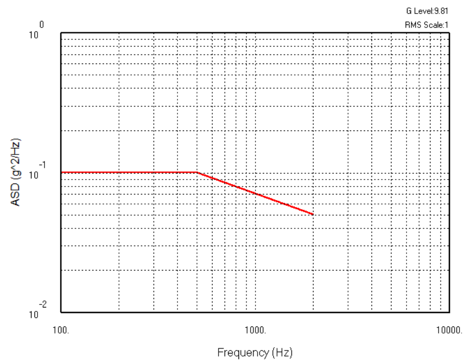

Figure 6: Acceleration Spectral Density (ASD) Input

4. Results

4.1. Mesh Refinement

Any numerical analysis has sources of errors that can compromise the validity of the results, one of them is directly connected with mesh discretization.

Generally increasing the number of elements is one way of guarantee the quality of the results.

To ensure static analysis convergence it was analysed the total strain energy contained on all elements, which is less influenced by stress concentrations since it shows a global property of the structure.

Another criteria used to verify the convergence was the maximum displacement (norm) occurring inside the quadrilateral region in the vicinity of 5 mm diameter holes. Intuitively this displacement will appear in the border of this region, which will be considered a region away from the holes. In the same region the strain energy density of this elements was analysed.

Another convergence study was made where the natural frequencies close to 3000Hz were analysed. The rationale for this second is to ensure that the results from forced random vibration, which will be calculated using the modal superposition, are the most accurate as possible.

Although this was an iterative process, the convergence analysis was performed considering the final material configuration for the deflector made of carbon fiber reinforced polymer. For a matter of brevity the convergence results for the thermal deflector made of carbon fiber reinforced carbon are not mentioned here, but the results were verified.

Since the heat shield has a circular geometry, it was necessary to impose a radial element edge length and an angular number of divisions. It is important to approach both to maintain an aspect ratio closer to unit. The coarser mesh has 5140 and the finest 262976 elements and it were considered 12 meshes for this study.

The static analysis, in this section, is conducted through the application of a 30G inertial acceleration in positive Y direction. It was observed the fast convergence of the solution, in fact, after a number of elements above approximately 50000 the solution does not change.

As above mentioned, the convergence of the maximum displacements in the vicinity of the holes was performed and it was observed a similar behaviour compared with the previous check.

The last convergence check on static analysis is the behaviour of the maximum strain energy density inside the quadrilateral area close to the holes. The maximum of the strain energy density will occur in a region very close to the holes. This results can be seen on Fig. 7.

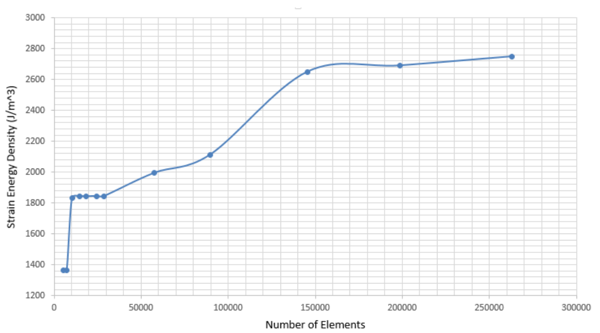

Figure 7: Convergence of maximum strain energy density in the vicinity of the holes

Based on these results, it is possible to see convergence, although much slower than the previous analysis. The main reason for this behaviour is the boundary conditions applied, which constrain excessively the deflector and causes high stress concentration in this region, increasing the strain energy density values of the elements in this region. Further observation about this issue will be done on section 4.4.

To check the convergence of modal analysis were analysed five modes of vibration (finest mesh numbering): mode 170, 172, 173, 174 and 176. These modes occur at frequencies close to 3000Hz. These results can be seen on Fig. 8.

Through the analysis of Fig. 8 it is possible to clearly see the convergence of the frequencies with the increasing of number of elements, although a small percentage of variation of results can be achieved only with high computational effort, and a trade-off study between the error and the time of computation has to be done Table 5. The calculated error is the maximum deviation obtained relatively the last analysis performed, which is the one with 262976 elements.

With 5140 elements, it takes 1.3 minutes to perform the analysis but the deviation is approximately 4% which will not be considered a reasonable value. The most accurate result is considered the last one, the most refined mesh,

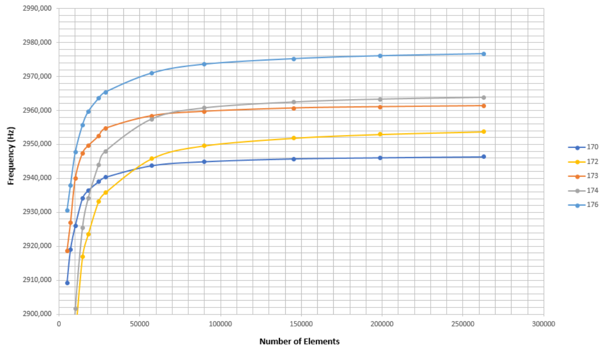

Figure 8: Convergence of modes frequency with number of elements

although this analysis takes 6.8 hours, which is not reasonable as well.

Table 5: Trade-Off study for mesh selection

No. Of Elm	Analysis Time (s)	$e_{maximum}$ (%)
5140	77	4,03
7276	89	2,95
10264	118	2,10
14712	179	1,29
18240	254	1,02
24624	390	0,70
28736	483	0,61
57396	1469	0,27
89696	2671	0,14
145376	6346	0,06
198796	14768	0,03
262976	24704	0,00

Based on all the results obtained (neglecting the strain energy density convergence) the chosen mesh is the one with 57396 elements, with a running time of 24.5 minutes.

4.2. Material Optimization

The optimization process of a space component begins with the assurance of the natural frequency of the first mode of vibration above 150Hz (information provided by AST). For safety reasons, and considering the approximations of this model, this frequency will be increased for values closed to 170Hz. The procedure consisted in increasing the cork thickness and changing the number and orientation of the skins in the case of the CFRP composite. In the C/C composite, the trade-off study was made varying the Cork NL25 and C/C thickness.

4.2.1 Carbon Fiber Reinforced Polymer (CFRP)

The starting point of this analysis was based on a previous project of AST: core with 6mm and skins with two layers oriented -45 and 45 degrees (0.2 mm thickness each skin). The frequency of the first mode of vibration was 106.6Hz, which is below the requirement. The first trial to increase this value was increasing the cork thickness, maintaining the properties of the skins constant. The results are shown on Fig. 9.

Since the total thickness of the thermal deflector should be kept as low as possible, it does not justify increasing the thickness for unreasonable values. At this point the core thickness will be fixed on 10 mm (10.4 mm total composite thickness) with a first mode frequency of 123.5Hz. To achieve 170Hz further optimization is needed.

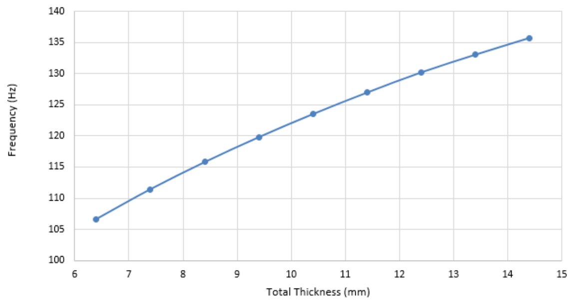

Figure 9: Influence of cork thickness on frequency of first mode of vibration

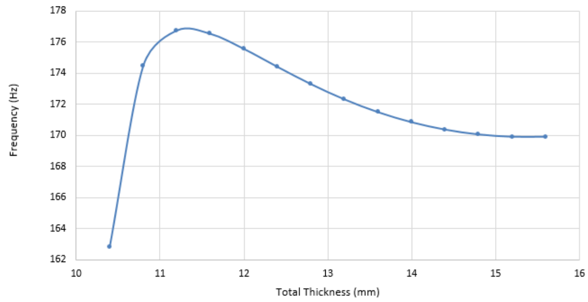

Figure 10: Influence of C/C thickness on frequency of first mode of vibration

The next analysis will be increasing the number of layers on each skin combining two types of layers (-45/45 and 0/90). The composite structure and the respective results can be seen on table 6-8.

Table 6: 4 layers

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Table 7: 6 layers

Removed due to confidentiality requirements

Table 8: 8 layers

Removed due to confidentiality requirements

As can be seen, it is possible to achieve the minimum requirement (150Hz) in all the analysis performed, although, the suitable choice would be the composite (*Removed due to confidentiality requirements*), since it lays on the safety side with a small increase in thickness.
The final material will have a total of 11.6 mm of thickness, being 10 mm of core cork NL25 and skins with 8 layers of 0.1 mm each made of carbon fiber.

4.2.2 Carbon Fiber Reinforced Carbon (C/C)

The starting point of this analysis was a core with 10 mm of thickness and 0.2 mm on each skin. The analysis was conducted through the increase of the thickness of C/C skins, starting in 0.2 mm and increasing in intervals of 0.2 mm until 2.8 mm. The results are provided on Fig. 10.

Through the previous analysis is possible to see an increase of frequency until values near 11.2 mm and a reduction after this thickness. Since it is desired to keep the thickness as low as possible and at 11.2 mm of total thickness the natural frequency of the first mode is 176.7Hz, it is possible to reduce the core thickness to achieve values close of 170Hz and keeping a margin of safety similar as the previous material analysed.

Reducing the core thickness to 9 mm it is obtained a first frequency of 171.3Hz, which is in accordance with the requirements defined. The final composite will have a total thickness of 10.2 mm, 0.6 mm on each skin of C/C and a core of 9 mm.

Summarizing the previous results, it is possible to see the final mass and thickness of both thermal deflectors:

Table 9: Mass and Thickness of Thermal Deflectors

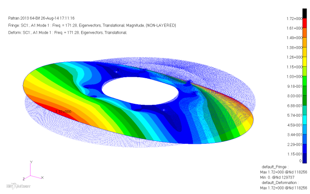
	CFRP	C/C
Total Thickness (mm)	11,6	10,2
Mass (kg)	1,43	1,26

4.3. Modal Analysis

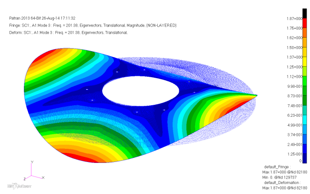
It was possible to observe that the natural frequencies for both deflectors were very closed to each other, such as the mode shapes obtained.

The first 4 non-symmetric mode shapes are shown on Fig. 11 for the carbon fiber reinforced carbon.

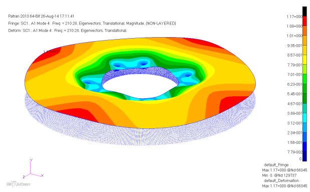
Only a small remark is needed on this analysis: mode shape of mode number 3 and 5 can look symmetric, although, due to the spacing of the holes and the existence of the block region, which confers more stiffness, mode number five presents a higher normal frequency.



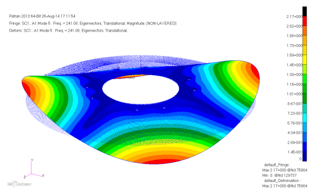
(a) Mode No. 1



(b) Mode No. 3



(c) Mode No. 4



(d) Mode No. 5

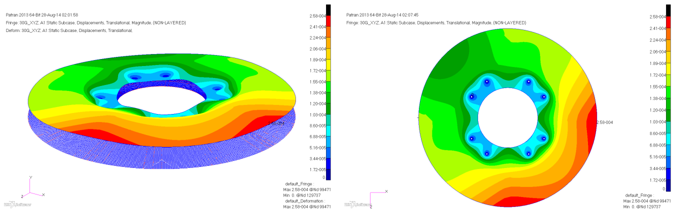
Figure 11: 4 first non-symmetric mode shapes for C/C thermal deflector

4.4. Static Analysis

The inputs given to the software are described on section 3.4.2. The objective of this section is to analyse the displacements and stresses distributions, and check if all the requirements are accomplished [13].

4.4.1 C/C Composite

The deformed deflector and the displacements are shown on Fig. 12. The maximum displacement (norm of the vector) is equal to 0.26 mm and occur at the outer diameter of the thermal deflector.



(a) Isometric View (b) Top View

Figure 12: Displacements field for a 30G Load positive on the three axis

The maximum stress occurs close to the 5 mm diameter holes. As shown on section 4.1, the results inside this region converge slower than the other analysis performed and with this mesh they are not converged. Further, the stress distribution inside this region is not realistic, since the edges of the holes are directly fixed, generating high stress concentration. To have useful information about this region a detailed analysis should be performed. For this reason, the stresses around this zone will be neglected. It is important to mention that the results provided by this analysis will be valid in the regions away from the holes, because the stress will tend to more realistic values.

The approach to analyse the overall behaviour of the thermal deflector under the previous loading conditions will be consider the failure indices, applying the Tsai-Hill criteria. All the values of yield strength (table 1 and 3) are considered with a safety factor of two. In Fig. 13 is shown the maximum failure indices on each element, independently of the layer.

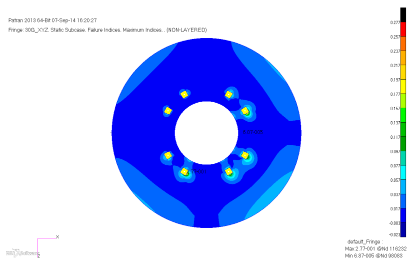
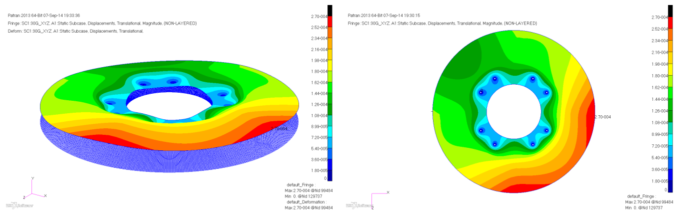


Figure 13: Maximum Failure Indices

It is possible to verify the maximum index is approximately 0.28, which is lower than one, implying that the deflector will not fail under this conditions. This value occurs on the first layer. To understand how far from failure this deflector is, the margin of safety was calculated and has a value of 1.03. This deflector, made of carbon fiber reinforced carbon, fulfils all the requirements imposed with an high level of confidence.

4.4.2 CFRP Composite

The procedures for the analysis of this thermal deflector are similar of the previous material, although a few details mentioned in the previous section will be skipped. As can be seen on Fig. 14, the displacements field is similar to the carbon-carbon deflector and the magnitude of the maximum displacement is 0.27 mm.



(a) Isometric View (b) Top View

Figure 14: CFRP Displacements field for a 30G Load positive on the three axis

The stress analysis was conducted on the same way as the previous section, and the stresses close to the holes were neglected. The results obtained for the maximum failure indices (considering a safety factor of two) on all elements away from holes are shown on Fig. 15.

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Figure 15: CFRP Maximum Failure Indices

Is it possible to observe that the maximum failure index is approximately *Removed due to confidentiality requirements*, which is much smaller than one. This value appears in the cork layer and as a margin of safety of *Removed due to confidentiality requirements*. This deflectors made of carbon fiber reinforced polymer supports this conditions with high margins of safety.

4.5. Forced Vibration Analysis

4.5.1 Modes' Contribution

To analyse modes' contribution for the convergence of the response, two nodes were selected and it was studied for both load cases (longitudinal and lateral).

It was possible to observe convergence of the results for modes until 3000Hz. For this reason, on the subsequent analysis the solution will be computed based on modes until this value.

4.5.2 Frequency Response With Damping

It was analysed the response in several nodes to detect the possible maximum displacements and ensure fulfilment of the requirements. It was studied the orders of magnitude of the displacements in all directions (global x,y and z). The nodes selected are on table 10 and Fig. 16 and are representative of the system's behaviour.

Table 10: Selected Nodes for Frequency Response Analysis

	Internal Radius	External Radius
Input	130919	130919
0°	66856	66345
30°	71103	71686
60°	76243	76826
90°	81697	82180

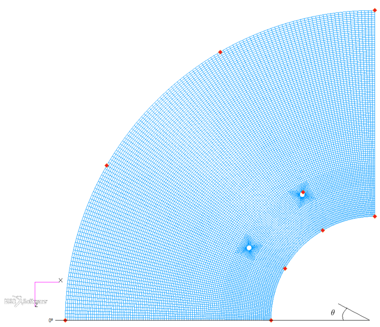
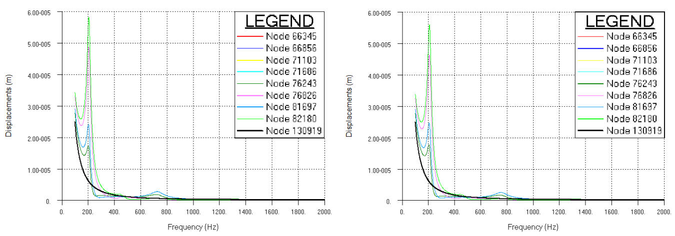


Figure 16: Selected Nodes for Frequency Response Analysis

Considering the longitudinal vibration, it was observed the dominance of Y displacements relative to the other two directions. In fact, X and Z displacements are an order of magnitude lower than the Y direction. The predominant movement occurs along Y direction, when the deflector is subjected to a longitudinal vibration. For this reason the response is shown only for Y direction Fig. 17.



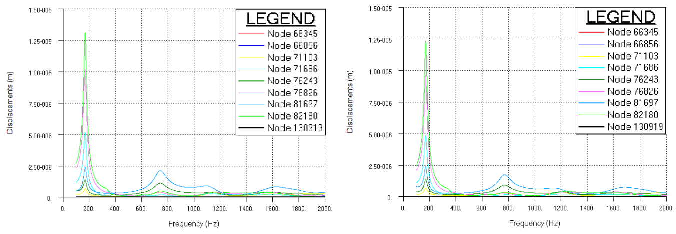
(a) CFRP (b) CC

Figure 17: Nodes Longitudinal Response 100-2000Hz Y

The maximum response in Y direction occurs on nodes 66345 and 82180 (external radius) for both deflectors. The maximum value for CFRP occurs at 205Hz with a displacement of 5.83E-5m and for CC at 208Hz with an amplitude of 5.58E-5m.

Considering the longitudinal vibration, it was also observed the dominance of Y displacements relative to the other two directions. For this reason the response is shown only for Y direction Fig. 18

The peak response in Y direction occurs at a frequency of 168Hz and a displacement of 1.31E-5m for CFRP and at 170Hz with a corresponding displacement of 1.23E-5m for the CC deflector.



(a) CFRP (b) CC

Figure 18: Nodes Lateral Response 100-2000Hz Y

4.5.3 Random Vibration

Since the PSD applied would be the same for both excitations and the amplification of the response is considerably higher in the longitudinal case, if the requirements are fulfilled for the longitudinal vibration there is no need to perform this analysis for the lateral vibration.

Based on previous analysis, due to symmetry, it is possible to exclude some nodes of table 10: Node 76243, 76826, 81697, 82180.

The displacements assume a statistical behaviour with a Gaussian probability density function, with zero mean. The 1 sigma (1σ) probability can be seen as the probability of the displacements x being between $-x_{RMS} < x < x_{RMS}$, and is equal to 68.3%. Following the same logic is possible to define the 2σ and the 3σ probabilities, which are 95.4% and 99.7%, respectively.

It is also important to "remove" the rigid body motion (PSD displacements of Node 130919), since the important response are the relative (RMS) displacements.

These results (1σ)can be seen on table 11 and 12. It is also shown the 2σ and 3σ displacements (meters). To easily understand these tables, e.g. for node 66345 the probability of the displacement exceeds $1.15E^{-4}$m is equal to $100 - 68.3 = 31.7\%$.

Table 11: CFRP Statistical Displacements

Node	1σ	2σ	3σ
66345	1,15E-04	2,30E-04	3,45E-04
66856	4,51E-05	9,02E-05	1,35E-04
71103	2,97E-05	5,93E-05	8,90E-05
71686	9,52E-05	1,90E-04	2,86E-04
130919	0	0	0

Table 12: CC Statistical Displacements

Node	1σ	2σ	3σ
66345	1,11E-04	2,23E-04	3,34E-04
66856	4,65E-05	9,29E-05	1,39E-04
71103	3,08E-05	6,16E-05	9,23E-05
71686	9,10E-05	1,82E-04	2,73E-04
130919	0	0	0

All of these values are bellow the requirements defined previously and both deflectors will withstand the random solicitation.

5. Conclusions

Two thermal deflectors made of carbon fibers and cork sandwich composites were studied in order to ensure the structural integrity. Both deflectors had, as core, cork NL25 and two options were proposed for the skins: CFRP, due to previous experience of AST with this material and C/C composite, since the thermal environment can be severe and this material can stand a maximum service temperature around 1000 °C.

The major achievement of this project is the possibility of reducing the weight of the thermal deflectors in order of 76% in the case of CFRP deflector and around 79% of C/C deflector, when comparing with the current stainless steel deflectors.

Based on the initial requirements, to achieve a reversible assembling mechanism, a design concept of the thermal deflector was suggested and then analysed (structurally). To improve the results' accuracy, a mesh refinement was performed and convergence of several parameters was verified.

To achieve the requirements, an optimization process was developed based on core and skin's thickness and in the case of CFRP the orientation of the fibers was also taken into consideration. After this process, was possible to increase the first natural frequency to, approximately, 170Hz for both deflectors (CFRP and C/C composite).

The static analysis was carried out on all the deflector except in the holes' region and it was possible to verify high margins of safety for both deflectors.

A modal analysis was performed and it was extended to an harmonic vibration problem, to understand the dynamic behaviour of the deflectors through the modal superposition method. It was studied two loading conditions (longitudinal and lateral) and it was understood the influence on the response on all directions. The final dynamic analysis was the random vibration, which consisted in defining a random load and study the response in a statistical way. The results achieved were in accordance with the all the requirements defined.

For all these reasons is possible to conclude that both deflectors will survive to all the loads applied at the mechanical interface, and is expected to contribute for development of new space applications with carbon-cork sandwich composites in a near future.

5.1. Future Work

For future work the following steps can be suggested to achieve the fully concept validation:

• To validate the application of carbon fibers and cork sandwich composites in a thermal deflector the thermal requirements should be defined and a preliminary analysis should be performed.

• From a structural point of view, and giving continuity to this thesis, a few steps can be suggested, such as experimental dynamic analysis of plates made of these sandwich composites, in order to determine damping properties and achieve a correlation, improving the finite element model.

• If desired, a detailed structural analysis can be performed considering the interface between the quarters of the thermal deflector, including the M4 metallic sleeves and the M5 inserts at the mechanical interface with the spacecraft. A detailed stress analysis on bolts and the inserts should be done.

The thermal analysis and the improvement of the finite element model are essential to fully validate the concept of this project.

After the complete concept validation of the thermal deflector, the manufacturing process has to be taken into account, and it should be performed, to proceed with experimental tests (mechanical and thermal).

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