CFRP ELECTRONICS HOUSING FOR A SATELLITE

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ABSTRACT

The drive for continuous mass reductions in spacecraft structures has promoted the use of carbon fibre reinforced plastics. CFRP has excellent specific stiffness and strength, which makes it possible to construct lightweight structures. CFRP is typically used in applications where electrical, thermal and radiation protection properties are not decisive.

Spacecraft has several housings for electronics and equipment. These are typically made of aluminium. Electronics housing multifunctional performance requirements can also be met using composite materials.

In the course of an ESA/ESTEC technology study “Advanced Equipment Design (AED)” a novel concept for a CFRP electronics housing was developed. Thermal conductivity of the structure was managed with high conductivity pitch based carbon fibres. The selected K1100 fibre provides as a ply about four times higher thermal conductivity in the direction of fibres than typical aluminium alloys. PAN based carbon fibre M40J was used as structural fibre.

Electrical properties and particle radiation protection were managed with a metal foil inside the CFRP laminate. The primary material selection for the foil was wolfram due to its high radiation attenuation capability, mechanical characteristics, and its good thermal conductivity.

A breadboard model was designed and constructed for the ADPMS unit of PROBA 2 satellite. Design drivers were a considerable mass saving compared to equivalent aluminium housing, parts integration, minimising the number of aluminium parts and manufacturability of the parts. All essential requirements set for the aluminium housing were applied to the CFRP housing with no major modifications.

In the breadboard model the wolfram foil was replaced with a steel foil. However, sample tests were conducted to applicable wolfram embedded laminate structures to evaluate the radiation attenuation properties. The results indicated viability of the concept.

The external dimensions as well as the location of PCBs and connectors were determined by the requirements set for the aluminium housing. This restricted the freedom of design and resulted in some non-preferred design details. Limited space and strict tolerances gave challenge to the design, manufacture and assembly.

The finite element structural and thermal analyses were performed. Also, some radiation attenuation calculations and simulations were performed. The correlation between the modelled and measured performance was analysed.

The breadboard model was subjected to EMI/EMC, thermal and mechanical qualification tests. The test performance was promising but indicated need for certain design changes. The major problem was related to the original materials selection where K1100 fibre with polycyanate ester resin was selected. This turned out to be a poor selection due to very low adhesion strength of the K1100 fibre to the matrix material. This caused a strong tendency to a delamination type failure in the laminate.

It can be concluded that there is a considerable potential of mass saving over the aluminium housing when utilizing multiple properties of composite materials. However, the cost of the CFRP housing should be decreased, especially material and manufacturing costs.

1. INTRODUCTION

The ESA/ESTEC miniproject Advanced Equipment Design (AED) included four sub activities:

A. Lightweight housings for equipment units
B. Improved design of large compact equipment units
C. Multifunctional support panels for electronic equipment
D. Lightweight electronic boxes for SAR antennas

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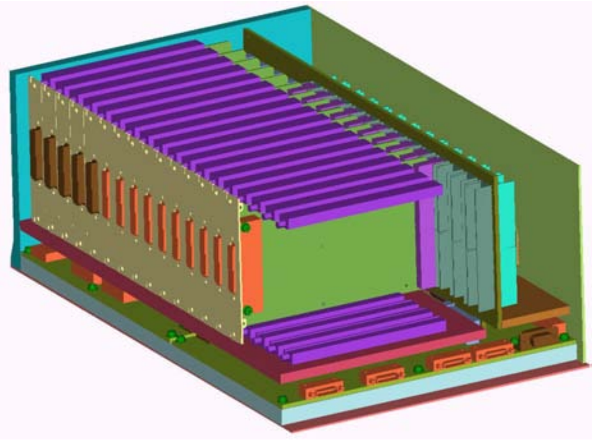
Sub activities A, C and D focused on CFRP structures which included carbon fibres with high thermal conductivity. Common prepreg materials were selected for all the sub activities. Based on performed material survey the following prepregs with polycyanate ester resin matrix RS-3C were selected:

- K1100 for thermal management
- M40J for structural purposes

The objective of sub activity A was to design and construct a composite breadboard model of existing aluminium electronics housing. First a reference application was selected. The selected housing was the Advanced Data and Power Management System (ADPMS) of the PROBA 2 satellite, see Fig. 1. The housing was in preliminary design phase when the study was started. The rationale was that the aluminium housing design is sufficiently ahead of the composite design and the composite housing design gets all the necessary design data in due time. The testing of both housings was scheduled to take place at same time.



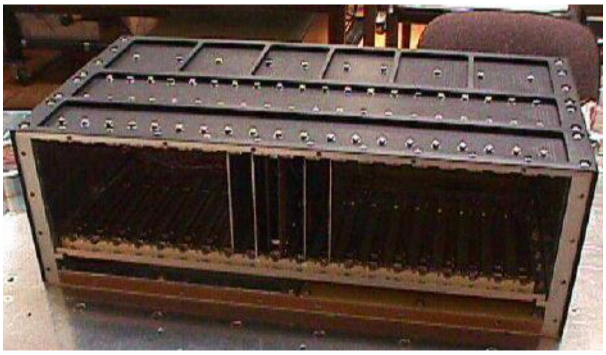


Fig. 1 CAD model (top) and the EQM model of ADPMS aluminium housing

The ADPMS housing is in size about 460 mm x 154 mm x 250 mm. One of the primary design drivers in the ADPMS was radiation protection. The prevailing wall thickness of the housing was 2 mm. The housing includes both power management and data handling PCB’s.

The requirements for the CFRP housing were derived from the requirements of the ADPMS housing. Basically, the requirements of the aluminium housing could be implemented to the CFRP housing without any major modification. In addition to mechanical and thermal requirements, also radiation and electrical requirements were identical.

2. DESIGN

The objective was to design a CFRP housing, which fulfils all the requirements set in the specification. The key design driver was a considerable mass saving, at minimum 20 %, over the aluminium housing.

All the electronic components, mainly PCB’s and connectors, had to be identical and their replacement should be equally easy in both housings. The internal dimensions of the housing were dictated by the dimensions of the PCB’s and the external dimension by the space allocated for the housing in the satellite. Thus there were very limited possibilities to change any dimensions in the design.

The general design drivers for the CFRP housing were:

1. Mass saving
2. Parts integration
3. Minimising the amount of metallic parts
4. Ease of manufacture

2.1 Design concept

The design concept was selected to minimise the number of aluminium parts and to implement parts integration as much as the accessibility of the housing allowed.

Thermal energy generated by electronics on PCB’s was transferred through the hat section, base panel and intermediate panel to mounting rails and from there to base plate or satellite structure, see Fig. 2. All the above mentioned composite parts included K1100 fibre for thermal management. Front and rear panels were not involved in heat transfer and they didn’t include any K1100 fibres.

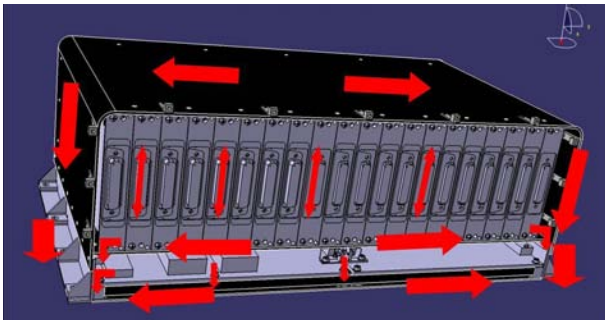


Fig. 2 Primary thermal paths.

The concept for particle radiation protection utilised so-called Low Z – High Z – Low Z concept, where the CFRP was the low Z material and wolfram the high Z material. The wolfram foil was the middle layer in all laminates forming the external surface of the housing. The wolfram foil was also used to provide electrically conductive layer in the laminate. The laminates were electrically conducted to each other with expanding rivets through the laminate, metallic inserts, steel bolts and copper stripes. The design is shown in Fig. 3 and the main parts are listed in Table 1.

The design included the following metallic parts: mounting rails for mounting the housing to the satellite, wedge locks to mount the PCB’s to the housing, fixation rails to lock the PCB’s and the rear panel connector plate to mount heavily loaded connectors. In addition aluminium and titanium inserts, monel and steel rivets and steel bolts were used.

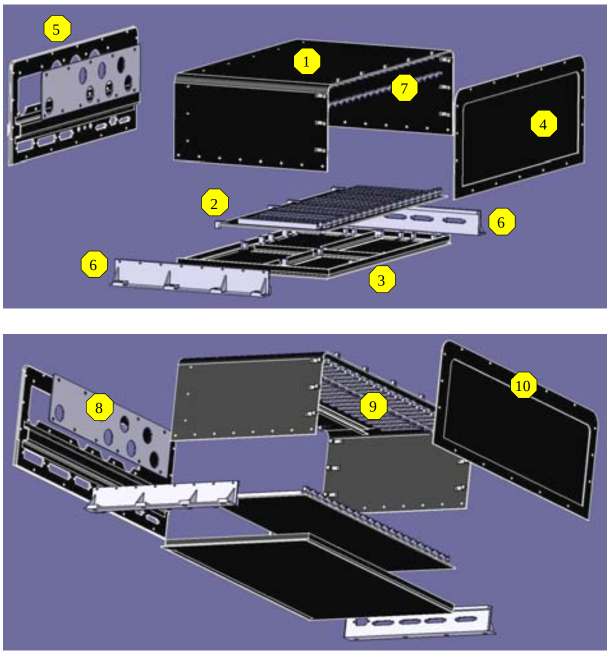


Fig. 3 Main parts of the composite housing

Table 1 Main parts

Part No	Part	Material
1	Hat section	CFRP
2	Intermediate panel and wedge locks	CFRP + Al
3	Base panel	CFRP
4	Front panel	CFRP
5	Rear panel	CFRP
6	Mounting rails	Al
7	Front connector, top fixation (Al)	Al
8	Rear panel connector plate (Al)	Al
9	Wedge locks	Al
10	Sleeve	CFRP

2.2 Analyses

The laminate structures were defined based on the following three main requirements:

- Adequate stiffness and strength with minimum mass
- Adequate thermal conductivity
- Adequate particle radiation protection

The laminate structures were analysed with ESAComp software and the structural and thermal analyses were performed using ANSYS finite element software.

As the common prepreg materials had been selected for all sub activities the laminate design was limited to those plies and a metallic foil. The fibre volume fraction of 60 % was used in design and analyses.

First the number of K1100 layers and their orientation was defined for the laminates that belonged to the thermal path of the housing. These laminates were the hat section, the intermediate panel and base panel. Based on the material data available during the design and analysis phase it was concluded that 4 to 5 layers of K1100 prepreg provides equal thermal conductivity to 2 mm of aluminium. As the laminate has the metallic foil inside it and the objective was to use symmetric and balanced laminate structures, 4 layers of K1100 prepreg was selected for above mentioned laminates.

The stiffness requirements dictated the number of required M40J layers. The orientation of both K1100 and M40J layers was defined based on laminate stiffness and Coefficient of Thermal Expansion CTE. CTE was important due to the reason that the design included aluminium wedge locks for the PCB attachment. These wedge locks were planned to be bonded to the laminate (hat section and intermediate panel). The reason for this was the desire to use the wedge locks as stiffeners and also to avoid drilling total of 120 holes to the hat section and to the intermediate panel. Due to intended bonding, the CTE of the laminate, especially in the longitudinal direction of the wedge lock, was an important design parameter, see Fig. 4.

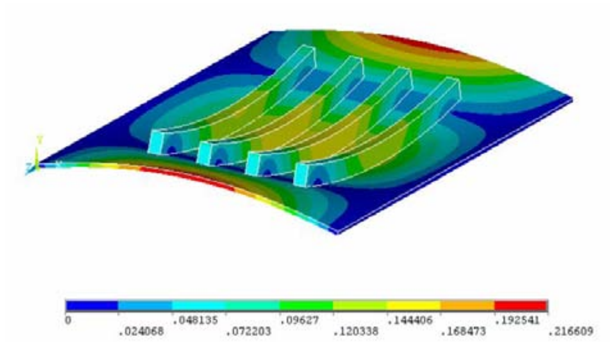


Fig. 4 Deformations due to wedge lock thermal mismatch to CFRP

The wedge locks reach only part of the depth of the hat section. Thus the thermal energy form the PCB's is mainly transferred to front two thirds of the hat section. To prevent large thermal gradients in the depth direction of the hat section the direction of the K1100 layers was defined. Thermal analyses together with mechanical analyses indicated that the K1100 layers should be positioned to +/-30° directions, see Fig. 5.

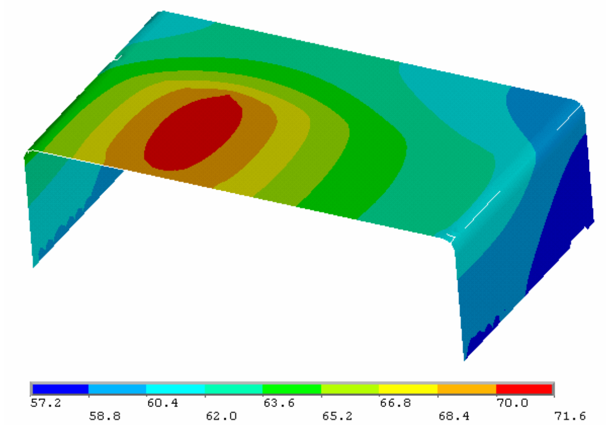


Fig. 5 Temperature distribution of the hat section

The front and rear panels are attached to the hat section with in-house designed inserts. The insert attachment points are strength critical. Especially interlaminar stresses are high at those points. The minimisation of interlaminar stresses was one of driving factors in definition of stacking sequence of the hat section laminate.

Primary radiation attenuation calculation based on handbook methods and to relatively simple analytical equations. Also, publicly available software was used over internet. Using these methods and the available material data it was concluded that a layer between 0.05 and 0.1 mm of wolfram would provide comparable radiation attenuation towards energetic electrons and protons as 2 mm of aluminium. However, due to uncertainty in the radiation protection concept, material values and analyses methods sample tests were performed. The tests are described in the following section.

Table 2 shows the laminate structures used in the housing with the laminate codes presented in Table 3.

Table 2 Laminate structure of main parts

Part	**t mm**	**Lay-up**
Hat section	1.92	[90a / +30b / –30b / +45a / –45a / +45a / –45a / St]SO
Intermediate panel	1.87	[90a / 0b / 0b / +45a / –45a / +45a / –45a]SE
Base panel	1.35	[30b / –30b / 90a / 0a / 90a / St]SO
Front panel	1.46	[0a / +45a / 90a / –45a / 0a / St]SO
Rear panel	2.02	[0a / 90a / 90a / 90a / 0a / +45a / –45a / St]SO

Table 3 Material codes of Table 2

Code	**Material**	**Layer thickness mm**
a	M40J/RS-3C	0.141
b	K1100/RS-3C	0.114
St	Steel foil	0.05
SO	Symmetric Odd	
SE	Symmetric Even	

3. SUPPORTING TESTS

The supporting tests performed by Helsinki University of Technology, Laboratory of Lightweight Structures (TKK/KRT) were the following:

- Manufacturing tests
- Metallic foil surface treatment tests
- Radiation attenuation tests
- Wedge lock bonding tests
- Insert strength test

3.1 Manufacturing tests

Manufacturing tests concentrated on the behaviour of the used prepreg materials. Especially, positioning a metal foil inside the laminate possessed challenges, which were managed with adequate number of manufacturing trials. Also, the bleeding and damming of laminates to reach the desired 60 fibre volume required trials.

3.2 Metallic foil surface treatment

The metallic foil inside the laminate is bonded to the surrounding CFRP with the matrix resin. To guarantee a solid and durable laminate structure the adhesion of the foil to the CFRP has to be adequate. In the early design phase wolfram was selected as a foil material. Due to availability and cost reasons the wolfram foils was replaced in the breadboard model with stainless steel foil.

The objective was to find as simple as possible surface treatment for both foils to provide adequate adhesion. From a limited number of tested treatments the following was selected:

1. Degrease with MEK
2. Grit blast with aluminium oxide
3. Degrease with MEK
4. Apply BR 127 primer

The adhesion was evaluated with Short Beam Shear (SBS) test. The results indicated adequate SBS strength with both foils. However, samples with wolfram foil indicated considerably higher strength than the samples with stainless steel foil.

3.3 Radiation attenuation

Two set of radiation tests were performed to verify analyses results. Test samples were representative but materials were not identical to the actual housing structure. In test samples CYTEC 977-2-36-12kIM7-189-11 prepreg was used. It is an epoxy matrix prepreg with IM carbon fibre. The fibre volume in the samples was about 55 %. Total of four samples were manufactured. Three of these samples had wolfram and one was a pure CFRP laminate. In the samples single wolfram layer (thickness of 0.05 mm) was used and in one sample double foil was used. In addition to composite test samples one aluminium reference sample (AA6082-T6, thickness 2.0 mm) was tested.

The radiation tests with electrons were conducted at Ghent University Irradiation Facility in Belgium and the tests with protons at Paul Scherrer Institute, Laboratory for Astrophysics in Switzerland. The nominal irradiation levels for electrons were 1.5 MeV, 2 MeV, 3 MeV and 5 MeV, and for protons 15 MeV, 17.5 MeV and 20 MeV. The levels were derived from the radiation profile of PROBA satellite.

The test results were not unambiguous, especially with electrons. This is because at higher energy levels there was considerable secondary radiation. This made direct attenuation comparisons impossible with the given data. However, at lower energy levels the proposed low Z – high Z – low Z concept with 50 µm wolfram provided better attenuation than 2.0 mm aluminium. The attenuation of protons with different samples is presented in Fig. 6.

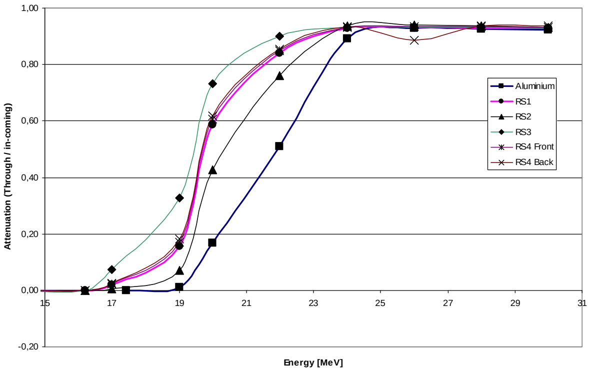


Fig. 6 Attenuation of protons

As the results needed some interpretation TKK/KRT turned to Helsinki Institute of Physics, which helped to clarify the test results. They studied the result and made same simulations using Geant4 software. The results of electron simulations together with the test results are presented in Fig. 7.

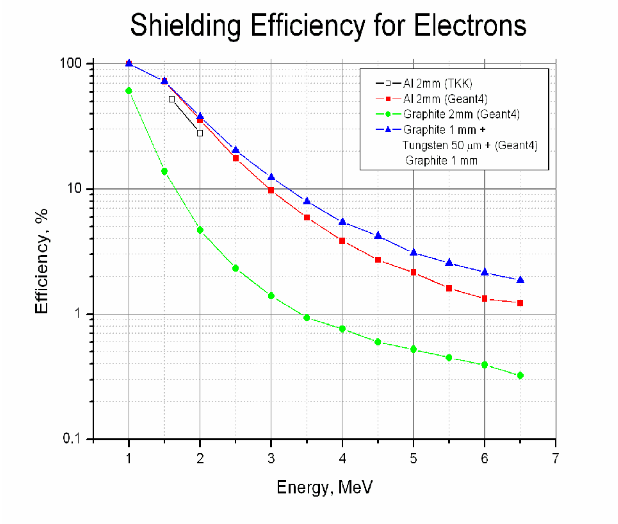


Fig. 7 Attenuation of electrons

As a summary it can be concluded that the applied concept provides better or equivalent protection against electrons as 2 mm of aluminium at studied energy range. However, it seems that even the double thickness of wolfram cannot provide as good protection against protons than 2 mm of aluminium. Based on test results and simulations the applied concept seemed to be valid and applicable to the ADPMS composite housing.

3.4 Wedge lock bonding tests

The primary obstacle in bonding the wedge locks to the CFRP laminate as structural members is the difference in thermal expansion between the aluminium wedge lock and CFRP. The bonding was planned to be preformed using an epoxy film adhesive, which had to be cured at 100°C minimum. Finite element simulations were performed to find out the deformations and joint stresses caused by the elevated temperature cure. Also representative wedge locks were bonded to a representative CFRP laminate. Based on the simulations and test bondings it became evident that the deformations of the CFRP plate with bonded wedge locks are too extensive even at room temperature.

To prevent thermal expansion of the wedge locks during the elevated temperature cure an invar tool was designed and constructed. The bonding trials with the tool indicated that the longitudinal expansion of the wedge locks could be restricted to acceptable level. However, the tool could not prevent the lateral expansion of the wedge locks well enough, thus the test laminate bended in the wedge lock transverse direction. This bending was very close to an acceptable limit but for minimising the risk of assembly it was decided to abandon bonding and to attach the wedge locks with bolts and room temperature curing paste adhesive.

3.5 Insert strength tests

In strength analysis the inserts attaching the front and rear panels to the hat section were identified to be critical. Due to uncertainties in modelling and material data the insert pull-out tests were performed. The inserts are made of titanium and they are specially designed for this application. The insert is bonded with paste adhesive to the hat section and attached with one rivet. The original design did not provide enough pull-out strength. The failure mode was the delamination of the CFRP. A modified insert was designed and manufactured. This insert had pull-out strength, which was very close to expected ultimate insert loads. The original and modified inserts are presented in Fig. 8.

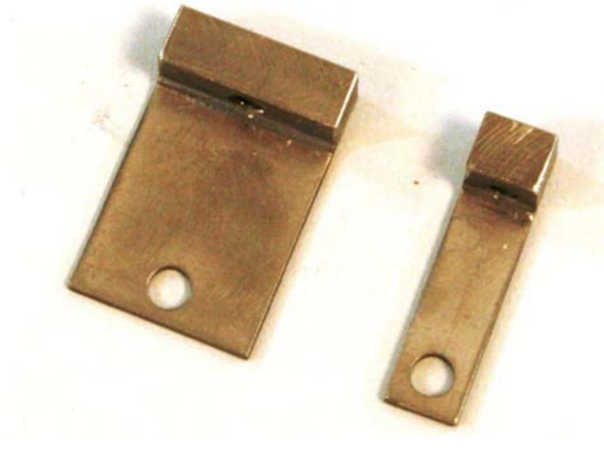


Fig. 8 Titanium inserts, original (right) and modified (left)

4. BREADBOARD MANUFACTURE

Required moulds and assembly tools were designed and manufactured. The moulds were:

1. Hat section mould, steel
2. Level mould for flat laminates, aluminium
3. Three closed moulds for stiffeners, aluminium

Especially the hat section mould was challenging due to close tolerances of the CFRP part. Thus, the mould was designed taking account to thermal expansion and the spring-back effect in the corners.

The main parts were manufactured in an autoclave while the stiffeners were manufactured in a press. The CFRP parts were machined to defined dimensions with a NC machine at an out-of-house machining shop. The same shop manufactured also the mounting rails and other aluminium parts excluding wedge locks and inserts.

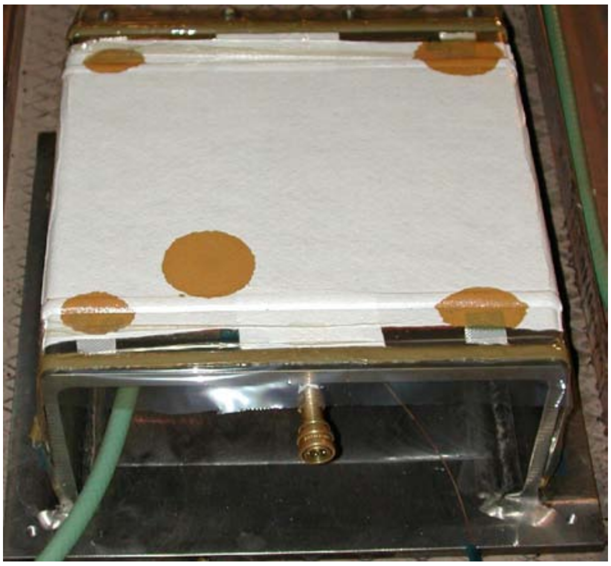


Fig. 9 Hat section in autoclave

The base panel, the hat section and the rear panel included bonded stiffeners. Special bonding tools were manufactured to provide accurate position and even pressure during bonding.

The inserts were bonded on the CFRP laminates. To guarantee accurate positioning of the inserts special tools were used in insert positioning.

The base panel is shown in Fig. 10. The copper stripes which electrically connected the metal foil to insert through a rivet can be seen in the figure. The housing with the rear panel removed is shown in Fig. 11 and the housing seen from the back side in Fig. 12.

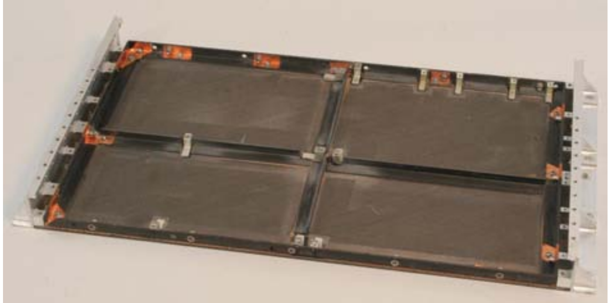


Fig. 10 Base panel with mounting rails

Fig. 11 Housing with rear panel removed

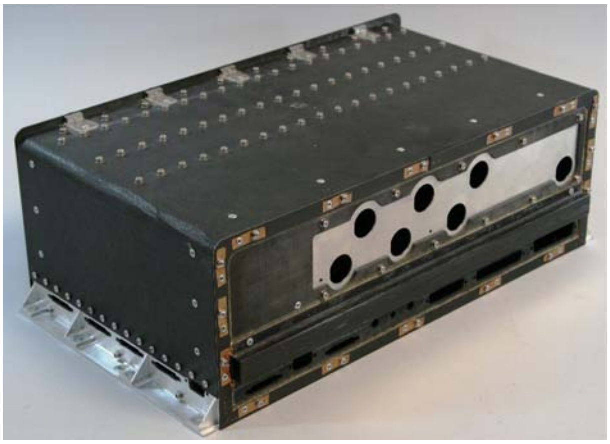


Fig. 12 Rear view of the housing

The realised CFRP housing was 29 % lighter than the corresponding aluminium housing.

5. BREADBOARD TESTS

5.1 Test program

To compare the performance of the CFRP bread-board with the Aluminium reference application, both housings were subjected to the following test:

- Thermal vacuum test
- Vibration test (resonance search, sine vibration, random vibration)
- EMI test (near field measurement)
- Electrical bonding test

5.2 Thermal performance

Thermal performance was analysed with ANSYS software and thermal balance tests were performed at ESTEC. Generally about 0.5 - 3°C higher temperatures were measured on PCB's in the composite housing than in aluminium housing. Temperature on external surface of the CFRP housing was at maximum about 5°C higher than on aluminium housing. In Chapter 6 test results are compared to analysis results with a thermal model representing the test configuration.

The thermal design of the composite housing seems viable. Some fine tuning is needed to meet or exceed the thermal behaviour of the aluminium housing. This tuning will have only modest effect on the total mass of the housing.

5.3 Mechanical performance

The vibration tests of the breadboard model were conducted at the Royal Military Academy in Brussels. The test configuration differed from the analysed configuration, because only a few plug-in PCB's were represented due to cost reasons and because the mass of the missing plug-in PCB's was distributed over the hat section.

This made the direct comparison of the test results to analyses results impossible. Later, a mechanical model with the test configuration was created and test results were compared to analyses results of this model. The comparison is presented in next chapter.

Furthermore some of the dummy masses in test configuration were larger than in the originally analysed configuration. The fact that only a few plug-in PCB's were mounted and the unfavourable location of some of the dummy masses, decreased the overall stiffness of the test setup and increased the test loads in respect to design loads. Fig. 13 shows the housing on the shaker and the coordinate system. The following conclusions can be made from the tests:

1. Lowest natural frequencies in X and Z directions were above the required 150 Hz
2. Lowest natural frequency in Y direction was below the required level. This can be due to the mounting arrangement of the housing to the shaker.
3. The housing passed sine vibration tests and random vibration tests at acceptance load levels in X and Z directions.
4. The sine vibration test in Y direction had to be aborted due to disintegration of certain inserts attaching the PCM PCB to the base panel.

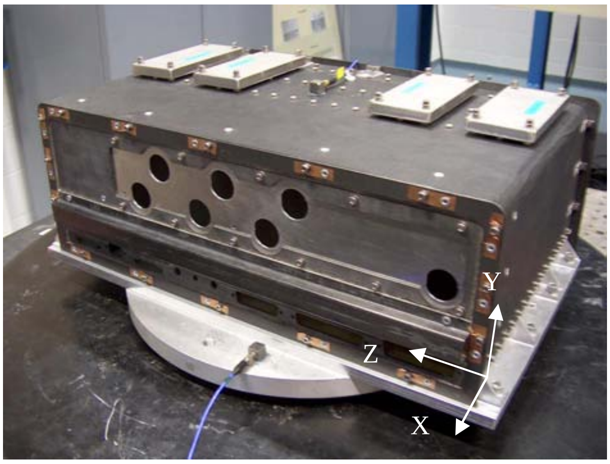


Fig. 13 Housing on the shaker

The disintegration of inserts was due to low interlaminar strength of the laminate. The inserts separated from the base panel so that the inserts had CFRP on their bond surface. Thus the bonding was durable but the laminate failed. Similar kind of delaminations could be detected under inserts that attach the front and rear panels to the hat section. No other structural damages were detected after the tests.

5.4 EMC performance

Electrical Bonding and EMC protection was realised using metal foil inside the laminate on all external surfaces. The metal foils in different panels were electrically conducted to each other with copper stripes, rivets, threaded inserts and steel bolts. The overall effort devoted to electrical design of the housing was modest.

For the EMC performance following conclusions can be made from the tests:

1. Dampening of magnetic field (H-field) was about 25 – 20 dB lower with the CFRP housing than with the aluminium housing.
2. Dampening of electrical field (E-field) was about equal with both housings although at high frequencies the CFRP housing was slightly better.

5.5 Electrical bonding

For the electrical bonding of the housing, a bonding resistance was measured about 10 times higher than the aluminium housing (50 mOhm compared to 5 mOhm) and the bonding requirement specification was not met.

Electrical bonding is a crucial requirement from the electronic equipment and it is clear that improving this electrical bonding is an area for further work/investigation. However, another conclusion could be that the CFRP design and electronics design should preferably be considered as an integrated activity.

During the AED test campaign, the copper zones (strips/layer) between rivets and bolts have been found very fragile and damage was observed.

6. TEST RESULTS VS. ANALYSES

Only thermal and mechanical behaviour of the housing was analysed. Electrical behaviour was only designed and tested while radiation protection was tested only on sample level.

6.1 Thermal analysis

Same base model was applied in thermal and structural analyses. Whereas in the structural model all details such as stiffeners, front and back cover were included, in the thermal model only structures that have significance in thermal energy transfer were retained.

In thin composite panels temperature distribution in laminate through-the-thickness direction is very uniform. Therefore, single layer orthotropic shell element with equivalent laminate properties can be used. Single layer shell element has only in-plane degrees of freedom. Laminate out-of-plane direction behaviour, i.e. bonded joints and mechanical interfaces, was modelled using one-dimensional thermal links.

Analysis input data was based on literature studies, as measured data did not exist in the course of the analysis. For example, contact conductance of 4000 W/m^{2}K was applied to CFRP laminate – aluminium mechanical joints. Hat section longitudinal conductivity was 115 W/mK and respectively, intermediate panel longitudinal conductivity 166 W/mK. The effective conductivity of laminate structures was around 20 % lower compared to aluminium housing. The loss in thermal conductivity and contact conductance was compensated introducing more bolts and using adhesive between wedge locks and laminates.

Both conduction and radiation heat transfer modes were considered. Original model was adjusted to correspond the test set-up. Cold plate and vacuum chamber shroud temperatures were set according to the thermal balance test. Heat generation of 22.6 W was applied on four thermally representative PCBs.

The FE thermal model gave very realistic results. Neither joint nor laminate properties could not be derived from test results due to the limited number and location of thermocouples. However, it can be assessed that bolted joints and laminate properties were modelled slightly conservatively. Respectively, wedge lock joints were optimistic. Temperature distribution of the hat section and intermediate panel is presented in Fig. 14.

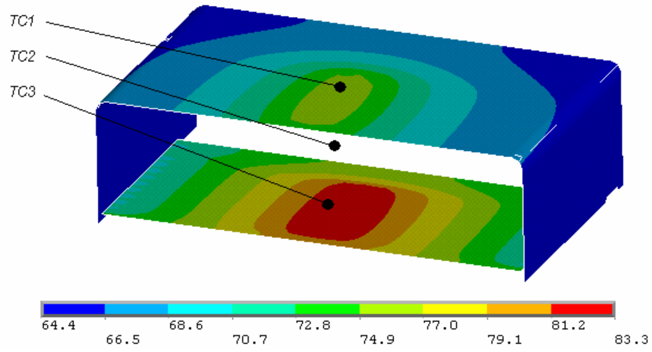


Fig. 14 Temperature distribution of hat section

Also, locations of three thermocouples are presented. TC2 refers to thermocouple 2 that is located in the middle of MPM PCB (not shown). Temperatures are summed up in Table 4.

Table 4 Analysed vs. measured temperatures

Item / temp [°C]	AED FE	AED test	ADPMS test
TC1	75,5	73,0	68,1
TC2	100,5	105,3	103,6
TC3	82,9	78,3	73,2
MPM mean	-	104,9	103,2

6.2 Mechanical analysis

In structural point of view the aim of the AED housing design was not to construct as stiff and as strong equipment as the aluminium counter part but just to meet the defined requirements in in-flight configuration. This meant that the AED equipment should present a first resonance frequency above 150 Hz minimum, and that the structure should show positive margin of safety against design loads.

For the quasi-static failure analysis the random load factor (RLF) was defined in the three directions. The RLF definition was based on the combination of low frequency and random vibration loads. The modified Miles' approach was used to obtain random load levels whereas max sine test level was considered as the low frequency load.

The FE model was built using quadratic layered structural shell elements and beam elements total element and node numbers being 56600 and 161200, respectively. Detailed FE failure post processing was performed using ESAComp. The input data was ANSYS shell element results.

Original analyses indicated the general feasibility of the design, but revealed the criticality of laminate interlaminar shear stresses close to inserts. Therefore, applied test levels were increased in stages. Moreover, as the test configuration differed from the design configuration this procedure was seen very important.

AED housing passed all tests at acceptance levels at the two in-plane directions. However, in the out-of-plane direction the equipment did not meet the stiffness and strength requirements. The FE model was modified to correspond with the actual test configuration. The modified model described well the test behaviour. The FE model is shown in Fig. 15. Some discrepancies existed in the support conditions between the FE model and the test set-up and therefore thorough comparison could not be made. For example, the housing support plate used in the out-of-plane direction excitation was quite flexible. In addition, the test set-up encountered natural frequencies of the housing support jig when excited in the X-direction.

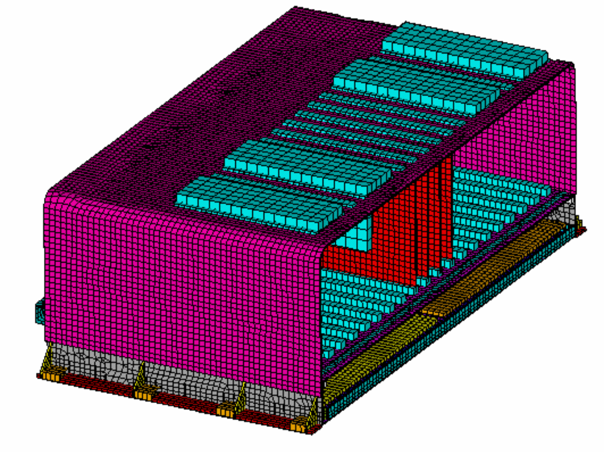


Fig. 15 The modified structural FE model

In the direction perpendicular to plug-in PCBs the FE model very well represented the reality after the PCB boundary conditions were changed from clamped to simply supported. Also, in the housing out-of-plane direction the accuracy of the FE model was good. In the X-direction correlation between the FE model and test results could not be found.

The model showed that the magnitude of the maximum insert peeling load was in the level of 200 N during the sinusoidal vibration test in the out-of-plane direction. That load is considerably higher than the load used in the design. Thus, the insert attachments were potential failure points.

7. CONCLUSIONS

The project indicated that using CFRP for electronic housings can lead to a significant mass benefit. The current bread-board has demonstrated a mass reduction of 29 %, whilst indicating that the CFRP housing can be at least equally competent on the structural, thermal, radiation and EMC requirements. Not all qualification tests were passed successfully and several issues were identified for further investigation. However, with some structural, design and manufacturing improvements, the CFRP housing can become a viable alternative for its aluminium counterpart.

Even more when one would consider to have an integrated design of both electronics and CFRP structure, the benefits of the CFRP could be further exploited (reduce further the number of parts) and the design can be further optimised from electrical, thermal and radiation point of view.

For large satellites, having on-board a lot of electronic housings, the use of CFRP could lead to a significant mass and cost saving at satellite level, considering that 1kg launched into space costs approximately (as rule of thumb) about 10000 Euros. This mass saving could be used to accommodate additional instruments/payloads or to store more on-board propellant for attitude and orbit maintenance thus extending the satellite operational life.

Due to the high material cost, the tooling cost and the more labour intensive manufacturing process, the CFRP housing is significantly more expensive than the aluminium housing (about 2.7 times the price of the aluminium housing). However, if one would be able to reduce the manufacturing cost and to use CFRP housings for electronic equipment which is used multiple copies on the same satellite (e.g. power & control electronics of active X-band SAR antenna) or on multiple satellites (e.g. telecommunication satellites, satellite constellation) the production process could be automated and the tooling cost could be reduced.

The following possibilities to further reduce the manufacturing costs have been identified:

1. Use more economic carbon fibre for thermal control. The thermal conductivity of the replacement fibre would be lower and by increasing the amount of that fibre the thermal requirements could be met.
2. Industrialisation of the manufacturing process.
3. Find other more economic metallic material to replace wolfram. The replacement material may cause some mass penalty in respect to wolfram.