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CMC thermal protection system for future reusable launch vehicles: Generic shingle technological maturation and tests

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Abstract

Experimental re-entry demonstrators are currently being developed in Europe, with the objective of increasing the technology readiness level (TRL) of technologies applicable to future reusable launch vehicles. Among these are the Pre-X programme, currently funded by CNES, the French Space Agency, and which is about to enter into development phase B, and the IXV, within the future launcher preparatory programme (FLPP) funded by ESA. One of the major technologies necessary for such vehicles is the thermal protection system (TPS), and in particular the ceramic matrix composites (CMC) based windward TPS.

In support of this goal, technology maturation activities named “generic shingle” were initiated beginning of 2003 by SPS, under a CNES contract, with the objective of performing a test campaign of a complete shingle of generic design, in preparation of the development of a re-entry experimental vehicle decided in Europe. The activities performed to date include: the design, manufacturing of two C/SiC panels, finite element model (FEM) calculation of the design, testing of technological samples extracted from a dedicated panel, mechanical pressure testing of a panel, and a complete study of the attachment system. Additional testing is currently under preparation on the panel equipped with its insulation, seal, attachment device, and representative portion of cold structure, to further assess its behaviour in environments relevant to its application

The paper will present the activities that will have been performed in 2006 on the prediction and preparation of these modal characterization, dynamic, acoustic as well as thermal and thermo-mechanical tests.

Results of these tests will be presented and the lessons learned will be discussed.

1. Shingle demonstration objectives

During the Pre-X preliminary study in 2001–2002, Snecma Propulsion Solide, entrusted with the responsibility of the high thermally loaded area of the windward side of Pre-X, proposed to design and provide the TPS using C/SiC based shingles. The use of large size shingles has been given particular attention.

In order to reduce the risks, a preparatory programme called “generic shingle” was initiated by CNES. It is

Abbreviations: C/SiC, carbon–silicon carbide composite; CMC, ceramic matrix composites; FEM, finite element model; HMS, health monitoring system; FLPP, future launcher preparatory programme; MMOD, micro-meteoroids and orbital debris; NDT, non-destructive testing; RCC, reinforced carbon/carbon; RLV, reusable launch vehicle; R&T, research & technology; TRL, technology readiness level; TPS, thermal protection system

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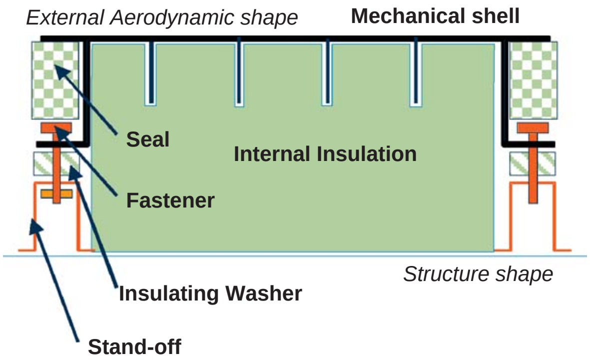

Fig. 1. TPS shingle concept.

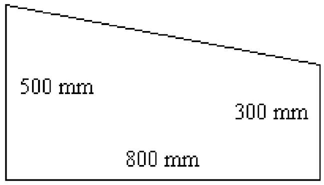

Fig. 2. Aerodynamic external shape of the panel of generic shingle.

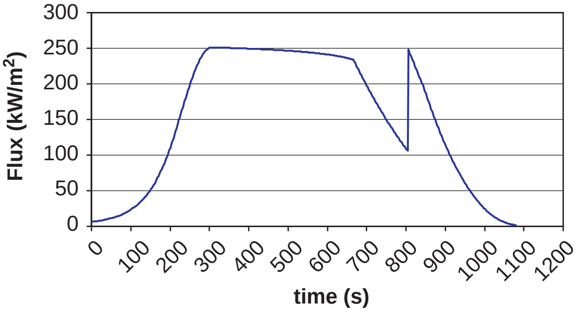

Fig. 3. Pre-X generic shingle reference flux.

based on the design, manufacturing and testing of a large shingle element. The main goal of this programme is to demonstrate the applicability of the improved technology to all the C/SiC shingle elements foreseen for the windward side of experimental re-entry vehicles. To support this demonstration, the following activities have been performed:

- design of the panel and attachments,
- analytical validations of the design,
- manufacturing of a complete large shingle,
- technological tests of the C/SiC panel's particularities,
- pressure and vibration test (sine, random, and acoustic) of the C/SiC panel,
- thermal testing, and
- thermo-mechanical testing.

2. Shingle concept description

This concept also called "shingle" is divided into two sets of elements:

- the ones with mechanical functions (mechanical shell, fasteners, and stand-offs) and
- the ones with thermal functions (inner insulation layers, seals, and insulating washers).

This is represented by Fig. 1.

The material needed for the mechanical shell has to be mechanically very efficient, and resist to highly constrained thermal environment; but its thermal conductivity characteristics are not the most important. The internal insulation and seals, not needing high mechanical properties, can be composed of low weight, flexible, and high performance insulating materials. The attachment system of the panel to the airframe structure must resist to relatively high temperatures, enable the thermal expansion of the panel, and transmit out-of-plane mechanical loads between the panel and the cold structure.

3. Main shingle requirements

The panel is to be manufactured with the same general requirements, same C/SiC material and same process as the ones foreseen for the Pre-X windward side shingles. As such, the requirements are derived from the specifications of the Pre-X TPS system and are summarized here after.

- Size of panel no smaller than an equivalent aerodynamic surface of $800\times400\,mm^2$.
- Ability to demonstrate the capacity to manufacture non-rectangular patterns as a minimum angle of 15° is necessary between the aerodynamic flow lines and edges of shingles. The approximate geometry is given in Fig. 2.
- Areal mass goal of $15\,kg/m^2$, the panel itself should weigh less than 2.3 kg.
- Ability to withstand the most severe heat flux and mechanical loads encountered on the windward side when fixed in a representative way to a rigid structure. The reference heat flux considered is provided in Fig. 3.
- Evolution of the flux on the generic shingle surface derived as a percentage of the reference flux. This evolution is provided in Fig. 4. Under this flux, the structure should be maintained under 150 °C.

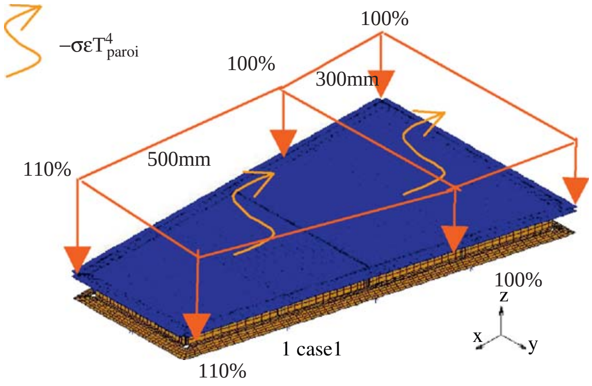

Fig. 4. Flux evolution on the aerodynamic surface of the generic shingle panel.

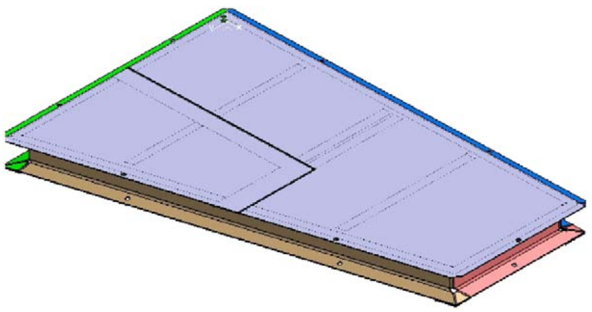

Fig. 5. Exterior view of the panel design, with the two skin sewn parts.

- Mechanical loads specified for the panel:
  - Pressure difference between the inside and outside of the shingle element is +100 mbar during take-off and −100 mbar during re-entry,
  - accelerations 10g in the panel plane and 5g normal to the panel plane,
  - dynamic loads considered as static accelerations of 15g in the panel plane and 10g normal to the panel plane,
  - acoustic spectrum derived from Ariane 5, and
  - flight loads, such as thermo-mechanical loads and deformation of the cold structure.

4. Panel design

In order to withstand the above requirements and to take into account the manufacturing process, the design of the panel is represented in Figs. 5 and 6.

The need for three stiffeners has been determined considering simple mechanical formulas. However, the need for nine attachment points has been established using FEM thermo-mechanical analysis. In addition, the interfaces between two adjacent panels is designed to take into account:

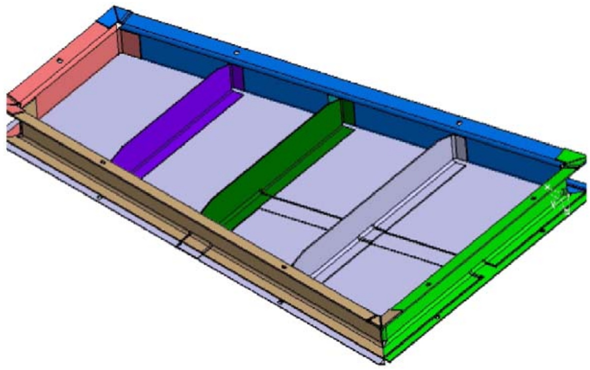

Fig. 6. Interior view of the panel design, with the edge and inside stiffeners. All links are textile sewing except for the stitched blue interior stiffener. (For interpretation of the references to the colour in this figure legend, the reader is referred to the web version of this article.)

- the reduction of the steps and gaps, in particular due to relative thermo-mechanical displacements and
- the ability to allow external access for integration and dismounting.

This led to a conceptual design of two-shingle interface represented in Fig. 7.

Finally, the design has been made in order to add as many manufacturing process validations as possible. That is why the skin of the panel was manufactured in two separate textile parts sewn together. This is not necessary for this specific panel size, but if larger parts are required, it may be of interest. In addition, two textile linking techniques were used to assemble the stiffeners to the skin: weaving and stitching.

5. Attachment system design

In order to attach the panel to the vehicle structure, a flexible attachment system has been designed. This system is able to fulfil the following functions:

- mechanically attach the panel to the structure,
- enable expansion differences between panel and structure by adapted flexibility of the stand-off,
- prevent large outer mould line deformation, through sufficient stiffness,
- participate to thermal protection of the structure,
- be mountable and dismountable without visibility through a small hole and without losing parts, and
- transfer loads from the panel to the structure.

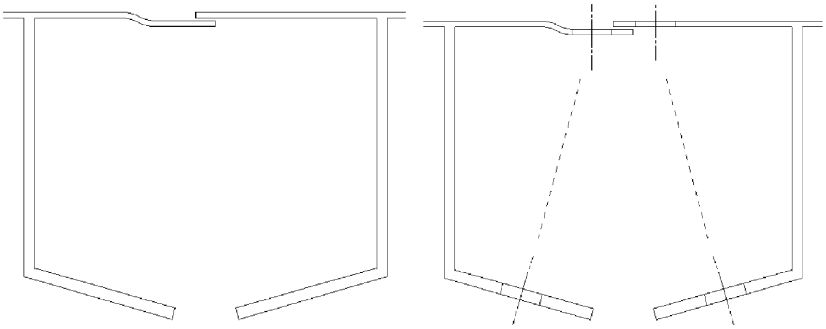

Fig. 7. Junction between two adjacent shingles on a standard area (left) and at an attachment point (right).

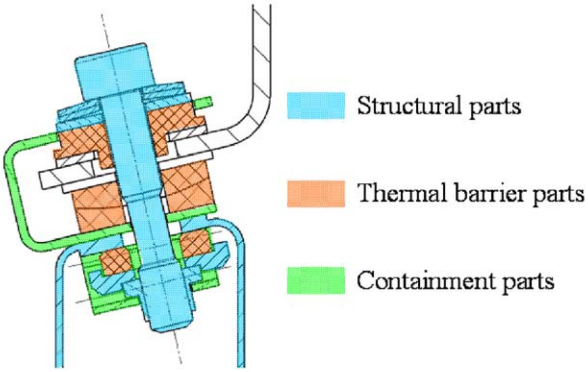

Fig. 8. Attachment configuration.

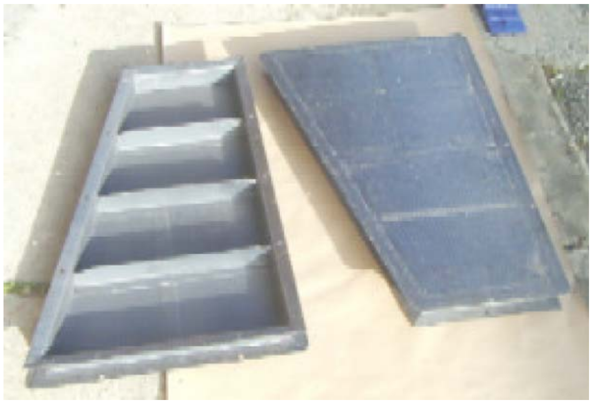

Fig. 9. The two manufactured generic shingle panels.

In order to fulfil these needs, the stand-off solution provides a two axis flexibility feature. Then, this stand-off is mechanically fixed to the structure while minimizing heat transfer. This implies the need of thermal washers. Elastic washers allow to maintain a correct tightening while the parts expand differently due to temperature. In order to comply with the accessibility needs even with no visibility, a system where all the washers are fixed to one of the parts (panel or stand-off and structure) before assembly has been designed. The resulting configuration is shown in Fig. 8.

6. Panel-components manufacturing

Two panels based on the design described above were manufactured. One was cut up to perform tests on particular local areas, to validate these particularities, and further refine the design of the shingle. The second one was kept intact and is currently used for testing. The manufacturing process is described below.

The production begins with the manufacturing of a carbon fibre carbon precursor reinforced preform. This preform is based on one ply multi-layer woven fabric which can be assembled by weaving to result in a self stiffened panel. The moulding of these panels is performed on a carbon/epoxy composite material mould able to withstand at least the temperature needed for the hardening process. This allows to reduce the thermal expansion mismatch between mould and part that can appear with metallic tooling. It also enables to increase the easiness of use by its low weight.

Then the preform is hardened by a liquid route. The silicon carbide matrix is added by CVI densification on a simple graphite frame holding the part. After grinding, de-burring and drilling of holes, the SiC CVI densification process is performed once again. It is also possible to add an oxidation protection coating if necessary (Fig. 9).

An infra-red NDI technique was applied to detect any potential defects, as shown in Fig. 10.

Apart from local lack of compacting of the preform, no additional defects were encountered. Overall density of the part is correct although slightly less than expected.

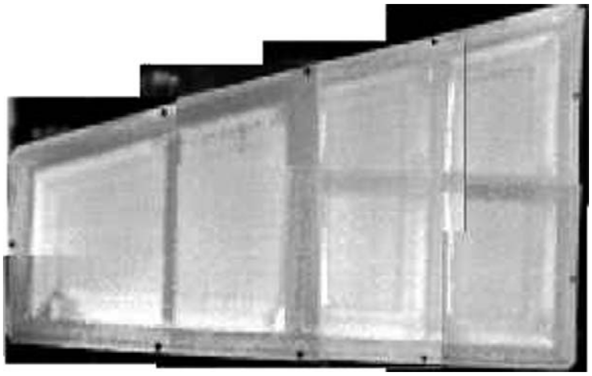

Fig. 10. NDI infra-red inspection of shingle panel.

Improvement of the compacting efficiency of the mould and higher overall density will be implemented on future productions.

The attachment system was procured, based on the design presented here above. The insulation is a commercially available off-the-shell silica/alumina felt. The seal around the panel is based on a silica/alumina felt inside a Nextel envelope, and was manufactured specifically to the geometry of the shingle.

Finally, the necessary metallic support structure for the various tests were procured, in order to be able to correctly interface with the test facilities, while remaining representative in terms of heat sink of the real cold structure for the thermal tests, and with a comparable rigidity for the dynamic tests.

7. Panel mechanical test

A mechanical pressure test has been carried out on the panel with the other components. The aim of this test was to validate the behaviour of the panel alone under representative loading. The flexible attachment is not included but an infinitely rigid condition is considered.

A FEM prediction of the test has been performed in order to take into consideration the specificities of the test and a factor of 1.3 on the load application has been considered necessary in order to be representative of flight mechanical loads.

It was foreseen to calibrate to 50 mbar the test applicability and hence make a preliminary settling of the panel material. Then the loading was to be slowly and incrementally increased up to a 130 mbar pressure difference representative of the 100 mbar in flight.

The observed airflow through the material porosity during calibration led to the conclusion that it would not be possible to reach the 130 mbar during test. A significant part of the leakage came from the local lack of compacting discussed before. Hence this leakage can be reduced for future panels. However, the total surface of the normal material also participates in the leakage, due to the inherent permeability of the material. This permeability contributes to the reduction of the in-flight re-entry pressure difference, and thus measurement of its value can help in evaluating the increase in design margins with regards to the current design.

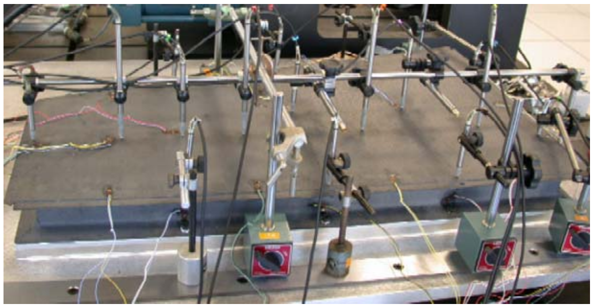

Fig. 11. Mechanical test of the C/SiC panel with all strain and displacement gauges.

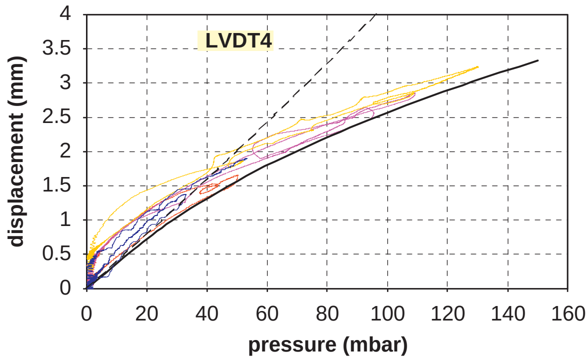

Fig. 12. Displacement gauges in the middle of the larger skin compartment for example (initial prediction in black dotted line, large displacement post analysis in black plain line, and different test runs in colour).

After artificially air-tightening the system with an internal flexible membrane an incremental load application was performed up to 130 mbar representative of the 100 mbar in flight (see Fig. 11).

After the test no failure of the panel was observed. A local damage is observed at approximately 90 mbar, which is consistent with the tests performed in previous phases. However, the analyses are conservative compared to the global behaviour during the test.

The displacements measured are lower than the ones predicted and the measured strain is also lower, as shown in Figs. 12 and 13.

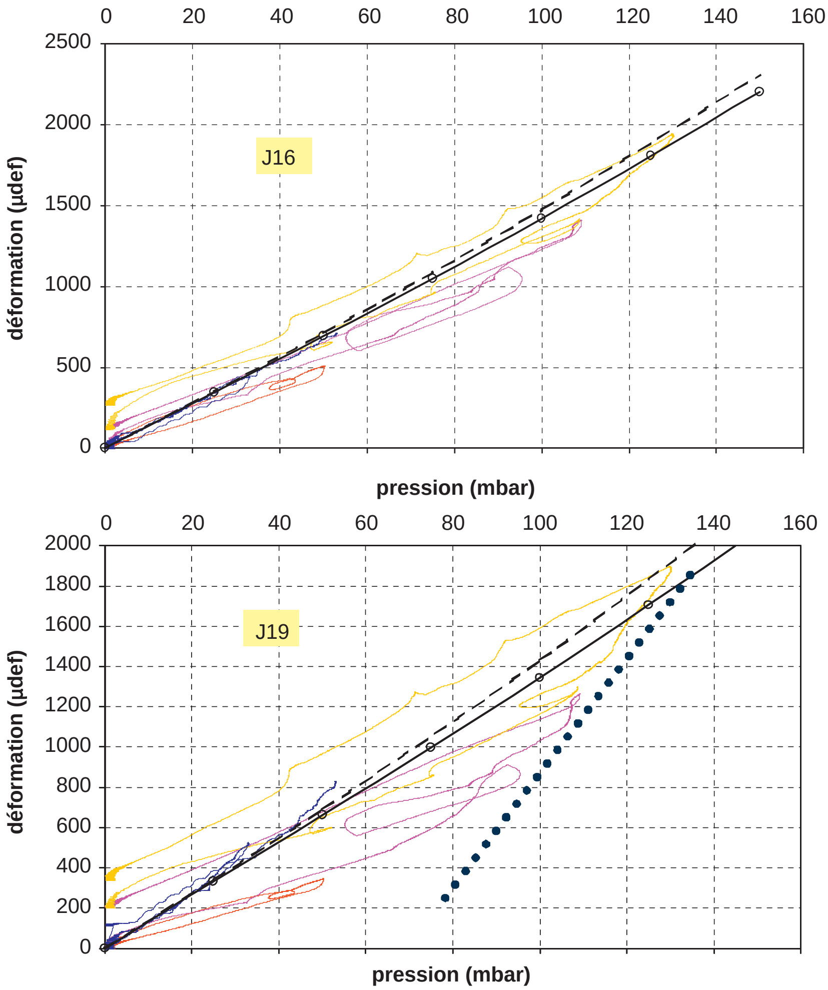

Fig. 13. Strain gauges on the longitudinal edge stiffener for example.

For example, the local damage, which was expected to occur at approximately 35 mbar, was observed at 90 mbar, and general damage, which was expected at approximately 107 mbar, did not occur.

In addition, the test results show that the analysis overestimates the deformation in the skin and in the angles, even the linear behaviour range of the material.

With the post-test data analysis performed, the maximum skin deflection expected in flight is no more than 3.7 mm with the current geometry, corresponding to a waviness of approximately 2%. The resulting margin of safety in the panel skin is greater than 0.86. In the frame angle regions, with a conservative approach, the margin of safety is expected to be positive. Only the attachment zone angle on the small frame very locally shows a negative margin of safety: as identified after design activities, an additional attachment point would be necessary if pressure levels specified are confirmed.

Refined evaluation of the behaviour will be performed during the thermo-mechanical post-test analysis.

8. Dynamic tests

All the dynamic tests have been performed at IABG test centre in Germany. These tests are based on the dynamic loading of the generic shingle, and the test campaign had the following objectives:

- provide information on the modal characteristics of the panel assembly with and without the insulation,
- validate the assembly to a given dynamic frequency spectrum, composed of different dynamic frequencies. The loading is oriented, on one hand in z direction, and in the other hand in x direction, and
- validate the assembly to a given acoustic spectrum.

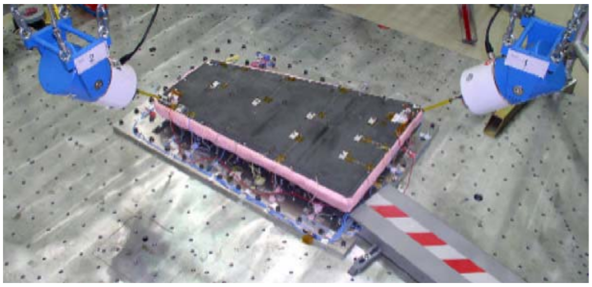

Fig. 14. Modal test set-up (credit IABG).

8.1. Modal test

With regards to the objectives of the modal test, the first modes of the assembly for frequencies ranging from low frequency (5 Hz) to 350 Hz have been investigated with and without the insulation material. The modal characteristics to be determined were the following:

- the eigen frequencies,
- the modal shapes, and
- the modal damping factors.

The test article (with attachments and seals) was placed on a rigid support, and excited at two different locations (see Fig. 14).

The measurements were well correlated with the predictions made from FEM analyses for the configuration without internal insulation, up to 200 Hz. The damping was slightly inferior to the arbitrary value taken in the model (0.4–1% instead of 1%). With the insulation, the behaviour of the equipped shingle was significantly altered: damping increased to 2.2% for overall displacement modes and to 5% for skin modes. Such high damping is generally considered beneficial as it ought to reduce the peak stress level under flight dynamic loads.

The frequencies were also slightly modified by the presence of the insulation, the first mode frequency shifting from 95 to 91 Hz. In both cases, the first modes are in-plane overall displacement modes linked to standoffs, while the first out-of-plane mode occurs at 115 Hz with the insulation and 122 Hz without the insulation as shown in Fig. 15.

8.2. Vibration test

The aim of the vibration test is to validate the shingle element up to flight load levels. Hence, the integrity of the system must be verified during the application of a representative dynamic loading.

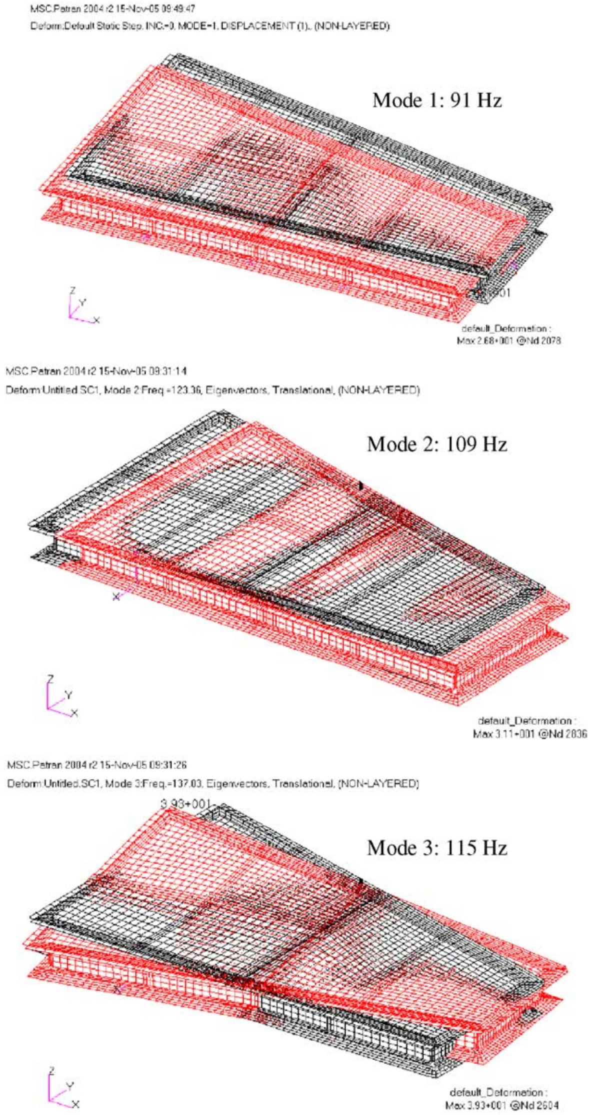

Fig. 15. Three first modes with corresponding frequencies (full shingle with insulation).

A predictive analysis has been performed, and notching has been implemented for certain frequencies, in order to limit the peak loads to acceptable values. This is justified by the fact that the dynamic load envelope is very severe (maximum loads from Ariane 5 environment), and by the fact that the panel had to survive the dynamic test to be able to be tested later under thermomechanical loads.

Two types of vibration solicitations have been assessed:

- sine vibrations, according to the load specification in Table 1 and

Table 1
Sine vibration load specification.

Frequency range (Hz)	Displacement or acceleration (peak)	Sweep rate
5–16	10 mm	1/3 oct/min ⇔ duration = 11.4′
16–60	10g	
60–70	22.5g	
70–200	22.5g	2 oct/min ⇔ duration = 2.4′

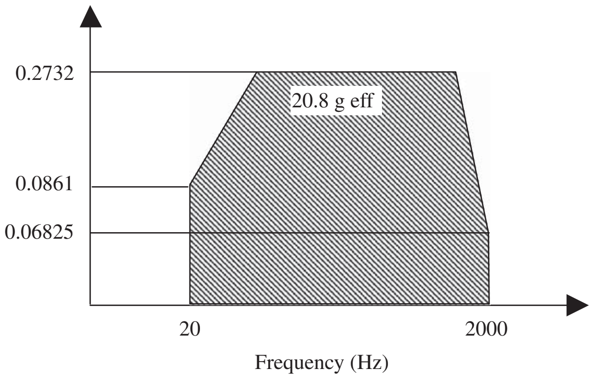

Fig. 16. Random vibration loads.

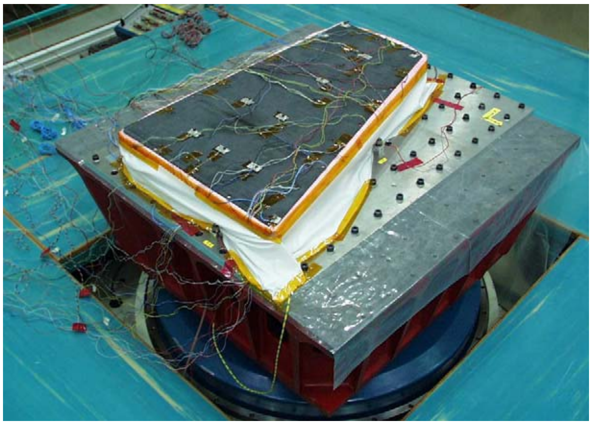

Fig. 17. Vibration test (credit IABG).

- random vibrations, with the loads described in Fig. 16.

The vibration test set-up, with again a completely equipped shingle is shown in Fig. 17.

The overall performance of the equipped panel was very satisfactory: the CMC panel withstood the loads without significant damage. The seal was moved out of its housing (see Fig. 18), which is not representative of the actual application. In the real case, they will indeed be pressed against the seals of the adjacent panels.

Fig. 18. Panel after vibration tests (credit IABG).

Accelerometers and strain gauges results are currently under analysis. The general behaviour is consistent with expectations. Some discrepancies with the predictions at high frequency (500–2000 Hz) will however have to be investigated (cf. Fig. 19).

8.3. Acoustic test

The acoustic test has been performed very recently and its results are also under ongoing analysis. The acoustic spectrum of the application is defined in Table 2:

This spectrum has been progressively applied, with one step at specified loads of 145.9 dB OASPL, one at 154.8 dB and finally one at 158.9 dB.

The test set-up is shown in Fig. 20.

The overall behaviour was again satisfactory, with no evidence of damage during the test. The measured strains were also well within the CMC material allowable values. These very good results allow the continuation of the campaign with thermal and thermo-mechanical tests.

9. Thermal tests

These tests are based on the thermal loading of the generic shingle, and the test campaign had the following objectives:

- validate the overall thermal insulating function of the C/SiC shingle TPS concept separated from side shingle components,
- validate the thermal insulating function of the interface between two adjacent shingles,
- validate the thermal insulating function of an attachment system in a representative environment,

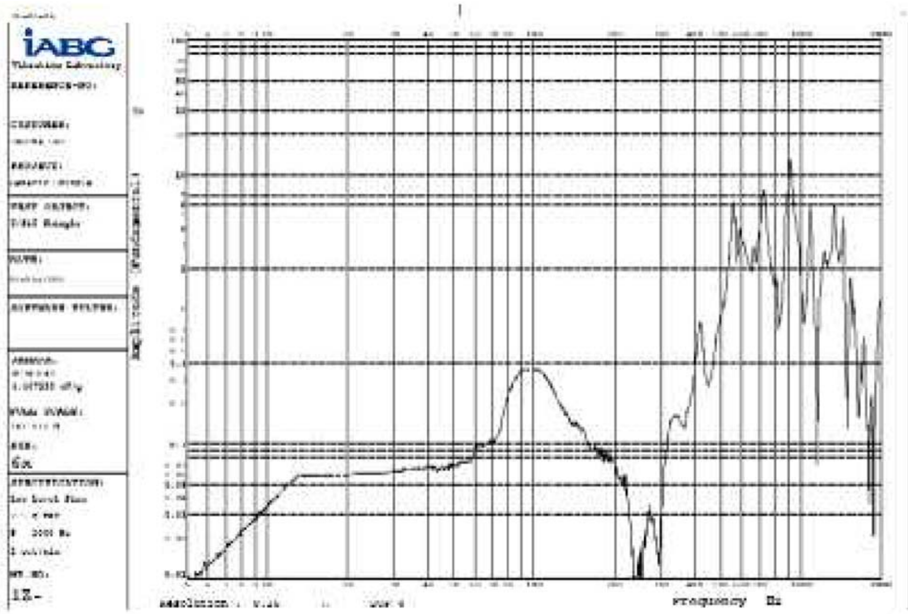

Fig. 19. Example of measured acceleration.

Table 2
Acoustic spectrum.

Octave bands (Hz)	Acoustic levels (dB)
31	154
63	153
125	152
1250	150
500	150
1000	150
2000	149
OASPL	160

- verify the thermo-mechanical impact of the thermal loading applied alone,
- feed-back to the FEM thermal calculation model accuracy by measuring the global thermal mapping, and
- verify the thermo-mechanical impact of the thermal loading combined with the mechanical loading.

The test article consists in the C/SiC panel attached to a representative cold structure by the means of nine attachment systems with its insulation and seal. In addition, in order to validate the interface between two adjacent shingle components, a portion of another C/SiC panel has been added (with its insulation, seal and attachment systems) on the side of the shingle that had previously been tested in dynamic environment, as shown in Fig. 21.

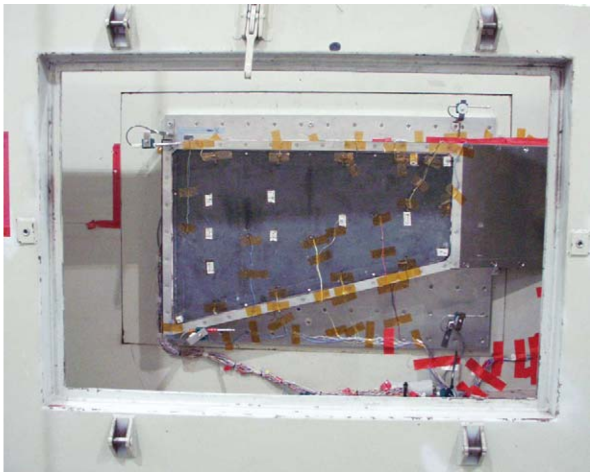

Fig. 20. Acoustic test (credit IABG).

The test article is attached to a thermal test plate which represents the thermal heat sink of the cold structure of a vehicle:

- volume of aluminium alloy representative of the corresponding vehicle structure aluminium alloy volume $\Rightarrow$ thickness 2 and 6 mm at stiffeners,
- interface holes M3 for attachment to the test means,
- venting holes to maintain the same level of pressure with the outside of the test-bed,

- DT hole access, and
- pressure sensor fixation and passages.

The assembled test article is shown in Fig. 22.

The thermal tests were performed in a step by step approach. A first pre-test was performed with a duration of 500 seconds during which an incident heat flux of $350\,kW\,m^{-2}$ was applied, corresponding to $280\,kW\,m^{-2}$ received by the shingle, as shown in Fig. 23 hereunder.

This pre-test allowed to verify the feasibility of the specified heat load application (especially for the cooling down phase), and confirmed the possibility to control the test by means of a flux-meter instead of a thermocouple, thereby providing better control precision. During this pre-test, it was determined that the temperature increase of the metallic attachments components was slower than expected, which allowed to proceed with a longer duration test. This pre-test was therefore followed by a full duration thermal test of 800 s, near the maximum planned duration of 1000 s. The initial results of this test confirm that the measured cold structure temperature remained below 100 °C.

A thermo-mechanical test was then performed on the shingle assembly, during which a pressure differential was applied on the skin at the same time it was thermally loaded. The thermal loading that was applied is the same as specified for the thermal test (cf. Fig. 23) with a heat application during 1000 seconds, and the pressure loading that was applied is indicated in Fig. 24.

The complete test article was placed inside a vacuum chamber in order to represent the re-entry environment. In order to be able to create a pressure differential on the skin panel at the same time as the thermal loading, a specific test set-up has been designed and manufactured

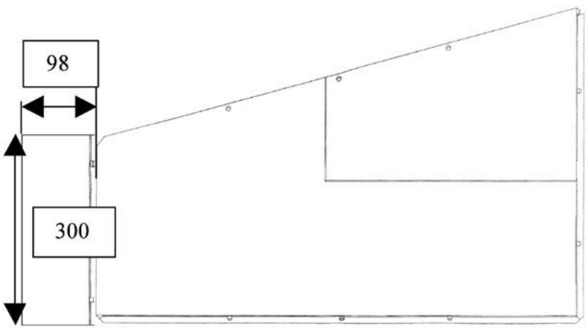

Fig. 21. Thermal test article.

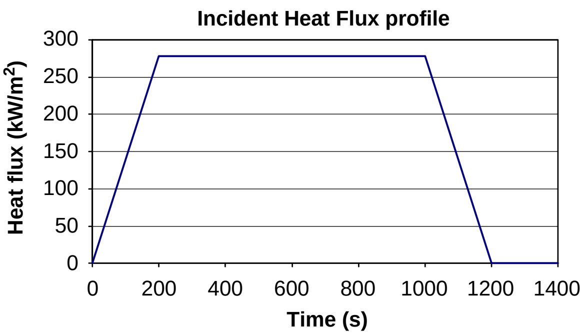

Fig. 23. Thermal profile specified for thermal tests.

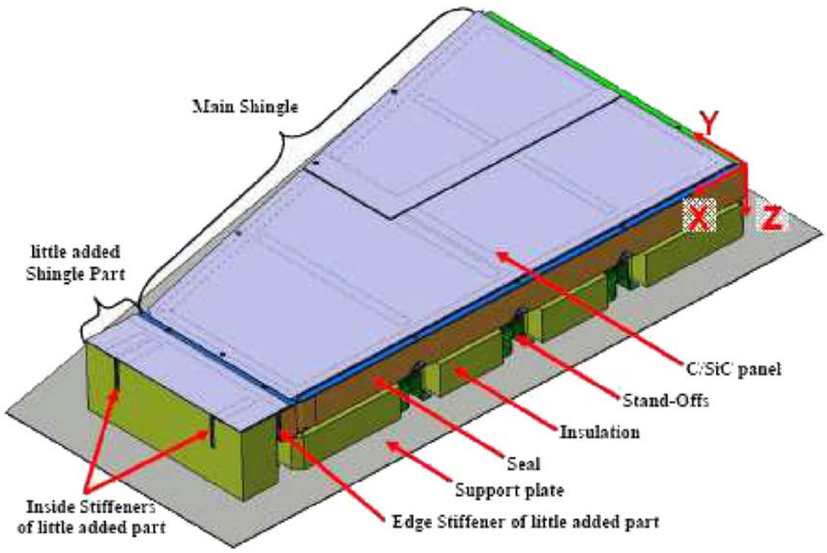

Fig. 22. Assembled test article.

by IABG, responsible for the performance of these tests. A presentation of the test set-up is shown in Fig. 25.

A first thermo-mechanical test was performed, but was stopped prematurely after 530 seconds, due to the failure during test of the flux-meter. This failure led to an overheating of the external skin of the shingle, which reached 1600 °C, compared to a nominal value of 1300 °C. As a consequence of this aborted test, the pressure was not applied for the thermo-mechanical loading in this run.

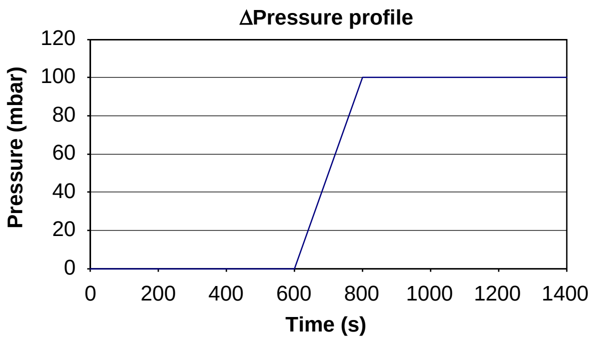

Fig. 24. Pressure profile for the thermo-mechanical test.

A second run was performed, the thermal conditions being controlled by a pyrometer instead of the flux-meter. This second run was successfully completed without further trouble, with the application of the heat-flux for 1000 seconds, and the combined application of the 100 mbar pressure load between the 700th and 2200th second. The test article is presented in Fig. 26.

Fig. 26. Test article ready for the thermo-mechanical test (credit IABG).

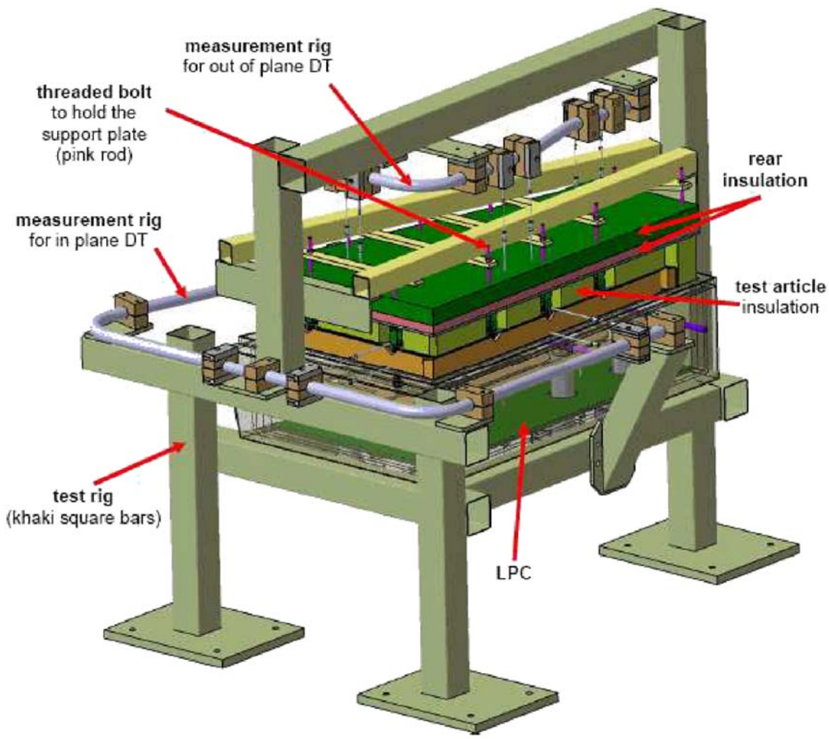

Fig. 25. Thermo-mechanical test set-up (credit IABG).

A preliminary analysis of the results confirmed the observations already made on the thermal tests. Moreover, the displacement measurements show that the values are somewhat higher than predicted during the thermal test, but slightly lower than predicted during the thermo-mechanical test. It is also noted that during the application of the pressure loading, there is a high level of forced convection, due to the fact that the pressure differential is performed by continuous injection of cold neutral gas. This convection, which would not be present in real flight conditions, induces a higher rate of heat propagation through the shingle thickness, but also a higher cooling rate once the incident heat-flux is stopped. This forced convection will be taken into account during detailed post-test analysis.

10. Conclusion

The generic shingle programme, a CNES funded programme started in 2003, has already demonstrated the ability to design and manufacture large C/SiC TPS elements using up-to-date materials and technologies. The next step, consisting in validating the resulting design, has now been achieved with the mechanical testing and dynamic validation performed on the panel, and the thermal and thermo-mechanical tests carried out.

The panel has successfully withstood a severe pressure differential load (130 mbar), as well as very demanding sine and random vibration loads. It was also tested in an acoustic chamber up to qualification loads without noticeable damage to the CMC panels or stand-offs. The seals were partially damaged, but their test configuration was very conservative, as they would be held into place by the surrounding panels' seals. The thermal and thermo-mechanical tests have provided valuable data on the behaviour of the shingle assembly under high temperature conditions, including with combined pressure loading. The results of this test campaign strongly enhances the validation level of this TPS technology.

Additional activities remain to be performed in the future, such as further enhancement of seals, insulation, attachment stand-offs and washers, and specific local C/SiC panel areas, as well as the analysis and test of pressurization/de-pressurization aspects.

With the results of the already performed test campaigns, and the additional activities proposed, the large shingle concept will have reached the technological maturity necessary for its use in the development of a full scale re-entry vehicle demonstrator.

Further reading

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