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CARBOTEX®-Si a CMC for hypersonic applications

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Abstract

Ceramic Matrix Composites (CMCs) are highly studied and used for the range of supersonic and hypersonic applications over the world. With the collaboration of ArianeGroup Gmbh (AGG), MBDA France has been developing such materials for hypersonic vehicles for more than two decades[(7)]. Since the early 2000s[1,2,3,4,5,6], MBDA, and its customer DGA, has selected the CARBOTEX® as the CMC that can be the structural material constituting scramjets, dual-mode ramjets and high speed air-breathing vehicles. This paper gives a short presentation on the CARBOTEX® and its variants (C/C and C/C-Si) and focuses on the studies that have been led over the last five years in the frame of manufacturing process optimization, material design understanding and thermo-mechanical characterization.

Keywords: *Ceramic Matrix Composite, CMC, Mechanical, Temperature, Scramjet, Carbon*

1. Presentation of CARBOTEX®

MBDA France is a recognized leader in design, development, manufacturing, integration and testing of missile systems in particular of hypersonic air breathing vehicles and dual-mode ramjets and related technologies. Hence, MBDA and its industrial partner AGG have developed a so-called "active cooling material" technology, the PTAH-SOCAR[3, 5] based on CARBOTEX® material, in order to sustain the extreme heat and mechanical conditions for several minutes during a hypersonic flight in the atmosphere. Therefore, the CARBOTEX® material has to fulfill many conditions in order to be fully operational, such as a high specific strength and a low permeability level.

CARBOTEX® is a carbon/carbon (C/C) CMC, braided in 2D with transversal and longitudinal fibers and reinforced in 3D by stitching yarns. As CARBOTEX® can be used for sandwich structures, the stitching operation is mandatory in order to ensure the mechanical connection between the different skins of the material.

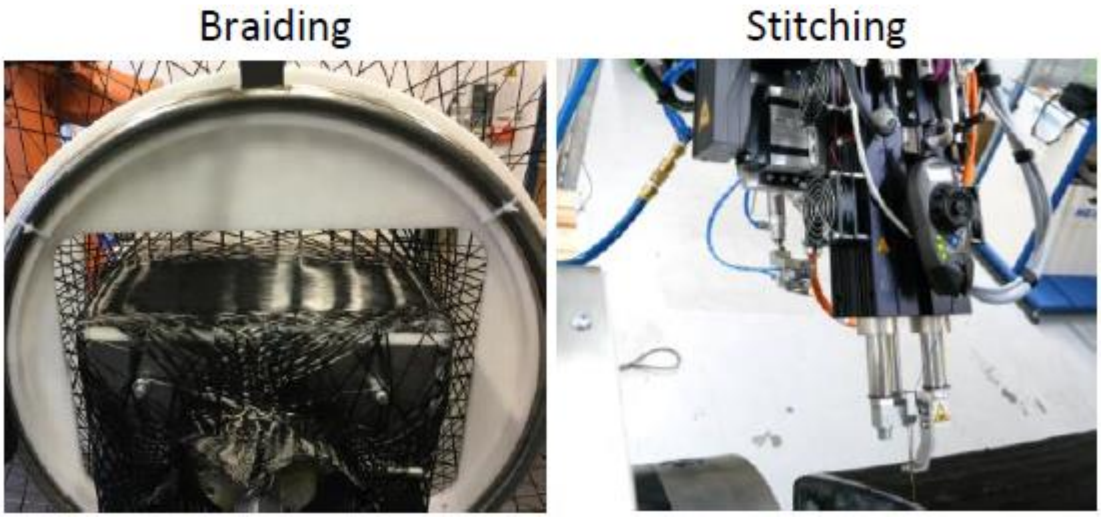


Fig. 1 Braiding and stitching operations

At that point, the CARBOTEX® is only at a carbon-fiber-reinforced polymer state (CFRP) and needs to be densified to reach the C/C state. Therefore, the matrix is infiltrated by a rapid chemical vapor infiltration (r-CVI) process in order to obtain a highly oriented carbon material[8].

Due to the external atmosphere constraints, an environmental barrier coating is needed to sustain the extreme heat load (>2000K) in the combustion chambers of hypersonic vehicles. This coating is performed by liquid silicon infiltration (LSI) in order to obtain a C/C-SiC state of CARBOTEX®.

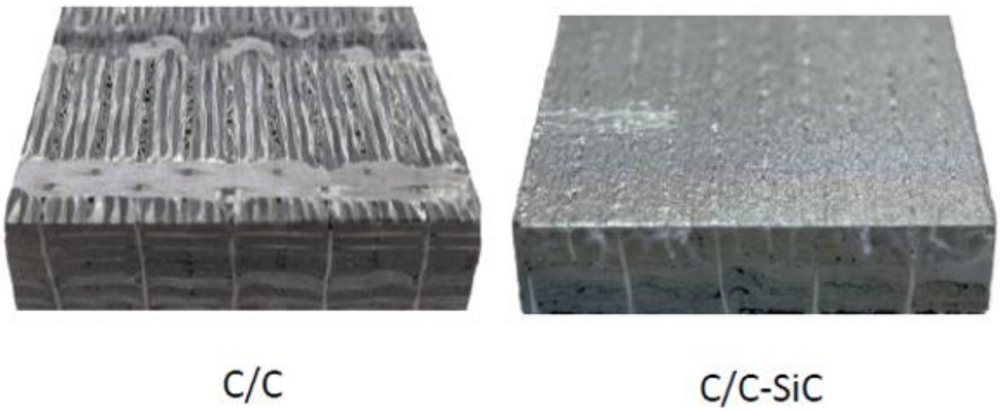


Fig. 2 CARBOTEX® samples at C/C state (left) and C/C-SiC (right)

Finally, to ensure an operational active cooling of the whole system the CARBOTEX® has to be tight and to present the lowest permeability as possible. In order to so, a solution is impregnated inside the material to fill up the pores. Hence, the CARBOTEX® reaches a C/C-Si* state called CARBOTEX®-Si* and is finalized.

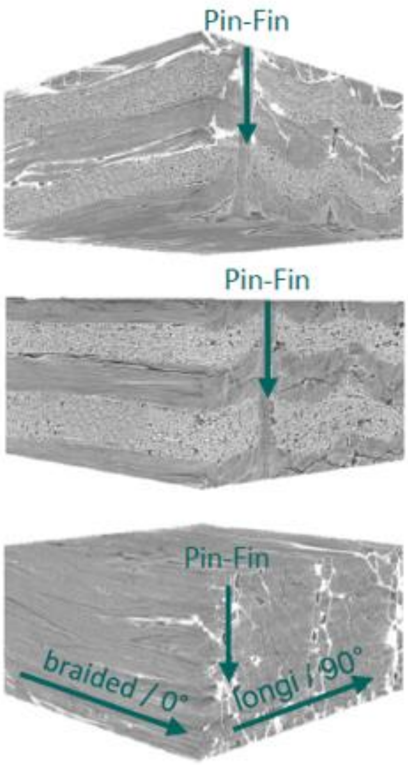


Fig. 3 CARBOTEX at C/C-Si* state

2. Manufacturing Process Optimization

2.1. The Different Fiber Architectures

The manufacturing process of CARBOTEX®-Si* is composed of many different steps. However, it can be decomposed into four main steps: textile preforming (yielding to the CFRP state), densification (yielding to the C/C state), siliconization (yielding to the C/C-Si state) and impregnation treatment (yielding to the C/C-Si*). Over the last years, each process has been optimized in order to gain on every characteristics of the material.

Textile preforming of CARBOTEX® has been the topics of several PhD hesis over the last five years, focusing on the study of braiding angles, stacking order and stitching operations. As high speed air-breathing propulsion combustion chambers can present complex internal and external shapes, the choice of braiding fibers was preferred against stacking.

In a first step, a preliminary study was performed to determine the effect of braiding on the mechanical properties of the material at C/C state. Eight different fiber architectures were studied through tensile tests at ambient temperature. Only two samples of each architecture were tested at that time, giving only qualitative results.

Among these architectures, three main types can be distinguished (shown in **Fig. 4**):

- Braid-Mesh : fibers along +/- XX° around 90° axis ;
- Braid-Longi : fibers along +/- xx° around 90° axis and along the 0° axis ;
- Braid-Longi with textile reinforcements (called "2F" or "3F") giving, locally, a higher fiber volume ratio.

(with XX and xx being whatever numbers between 0 and 90).

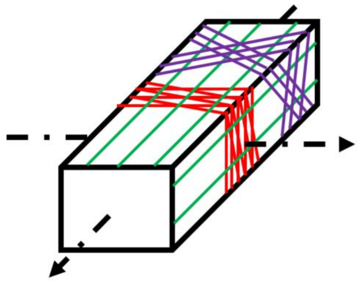


Fig. 4 Schematic of the braiding patterns

The effect of tufting was studied as well, with "not tufted", "half tufted" and "fully tufted" samples.

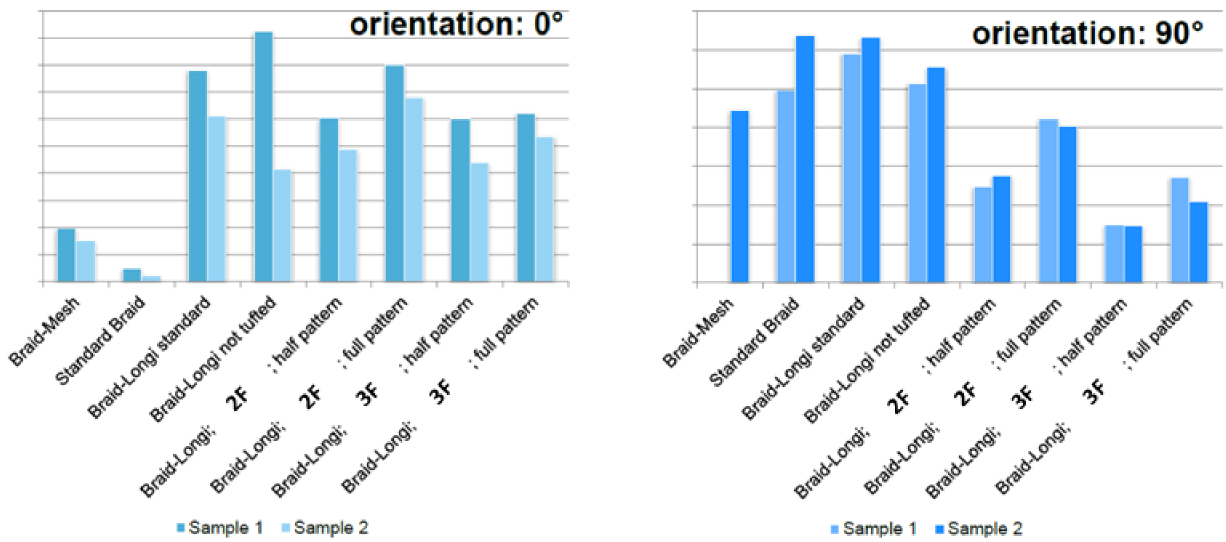


Fig. 5 Ultimate strength tests results

The **Fig. 5** shows the qualitative comparison between each fiber architecture in terms of ultimate strength. By taking into account the two orientations of mechanical loading (e.g. 0° and 90°), it is important to note that there is no "ideal" nor "perfect" fiber architecture. Depending on how the pressures and mechanical loads are distributed in the engine, the design engineers must choose wisely the type of CARBOTEX® needed.

The longitudinal fibers' presence shows a significant improvement of the mechanical strength in the longitudinal direction. It was also shown that a higher fiber volume content (FVC) tends to increase the strength in the longitudinal direction even more; however, it decreases significantly the performances in the 90° direction.

In addition, short-fiber textile reinforcements (called "2F" or "3F") can be added inside the material for mechanical purposes if necessary. As these reinforcements increase the FVC in the longitudinal direction, they also decrease significantly the mechanical properties in the transversal direction.

Hence, after iterative works and studies, MBDA France has selected different kinds of CARBOTEX® to constitute the different components composing high-speed air-breathing vehicles.

2.2. The Process Model

A multi-scale approach is used in order to better simulate and understand the CARBOTEX® material. However, as the benefits of a micro-scale model (e.g. interaction between the carbon matrix and the carbon fibers) cannot be accurately evaluated at the moment, a meso-scale modelling is chosen to better understand how the carbon fibers distribute in space. Then, a macro-scale model is used to simulate the mechanical behavior of the CARBOTEX® engines during hypersonic flights.

The meso-scale model, currently in development, will enable the design teams at AGG and MBDA France to better understand the physical interactions between the thermal loads and the mechanical loads taking into account the material characteristics' and the failure criteria.

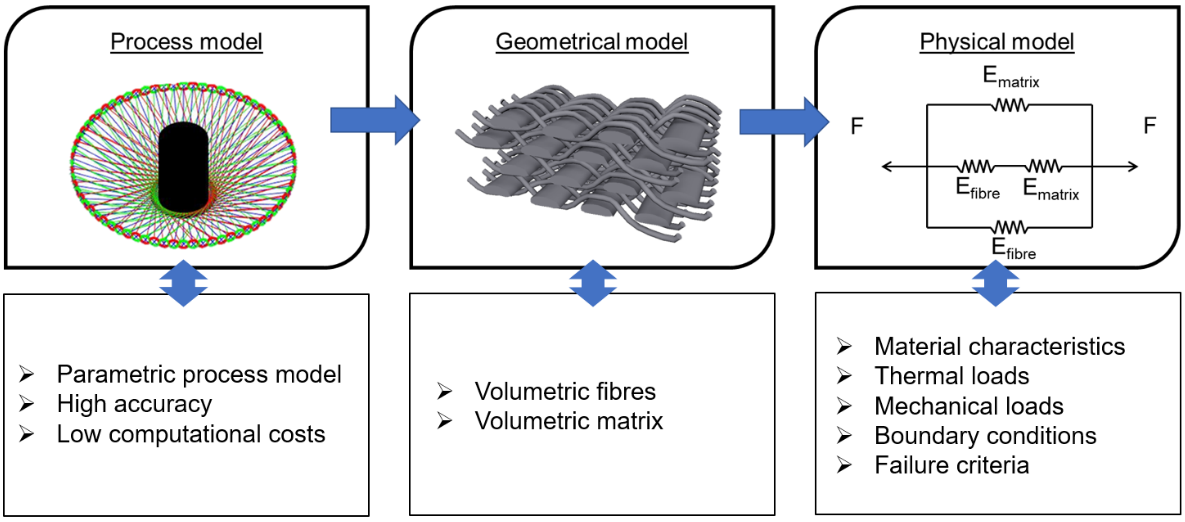


Fig. 6 The three sub-models constituting the meso-scale model of CARBOTEX®

As the geometrical model is currently in development, the following paragraph focuses on the process model.

The concept of the process model, created with the MATLAB software, consists of modelling the fiber architecture on the braiding core during the braiding operations. It is defined as follows:

- Inputs :
    - Machine parameters (diameter, number of bobbins) ;
    - CAD model of the braiding core rebuilt as a NURBS surface ;
    - Process parameters (rotation and translation speeds).
- Process :
    - The braiding process is modeled by computing each intersection point between the fibers enabling the creation of a NURBS surface corresponding to the braided structure.
- Output :
    - Volumetric model of the braided structure by fiber extrusion ;
    - The fiber angles at every single location on the part.

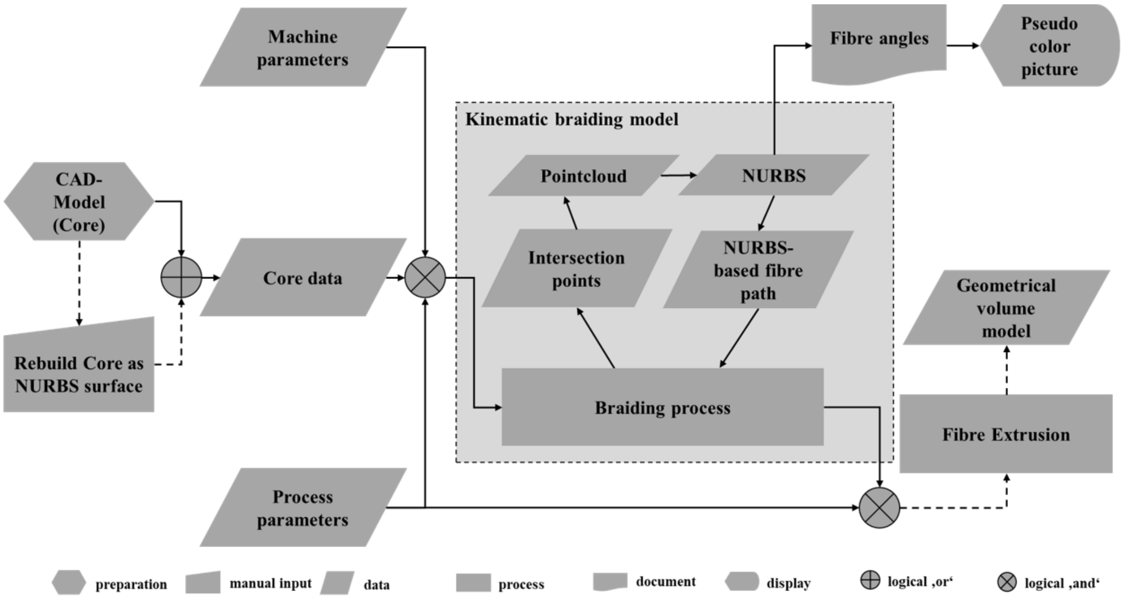


Fig. 7 Process model scheme

As depicted in **Fig. 7**, the process model simulates the braiding process by determining each fiber intersection points during the braiding. The first models were made by simulating an axisymmetric braiding core (**Fig. 8**).

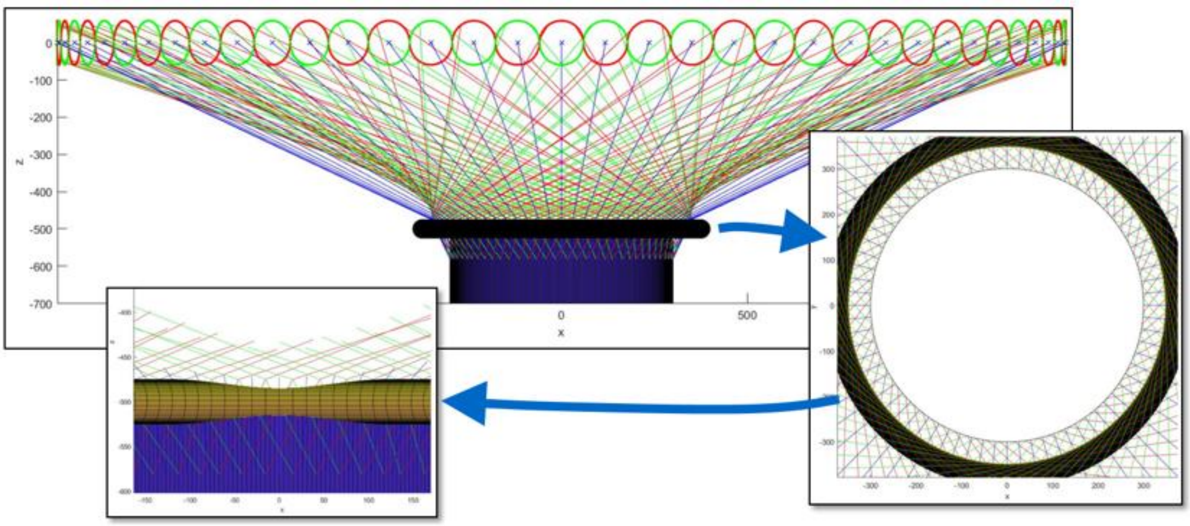


Fig. 8 Braiding simulation

Then, for a given braiding core, represented by a pointcloud, the fiber path can be determined along the core.
The simulative analysis (e.g. the process model's output) is computed on four different braiding cores, each one corresponding to different engine, or portions of engine, shapes (Fig.9): a cylindrical shape (a)), a "nozzle" shape (b)), a cuboid shape (c)) and a conical cuboid shape (d)).

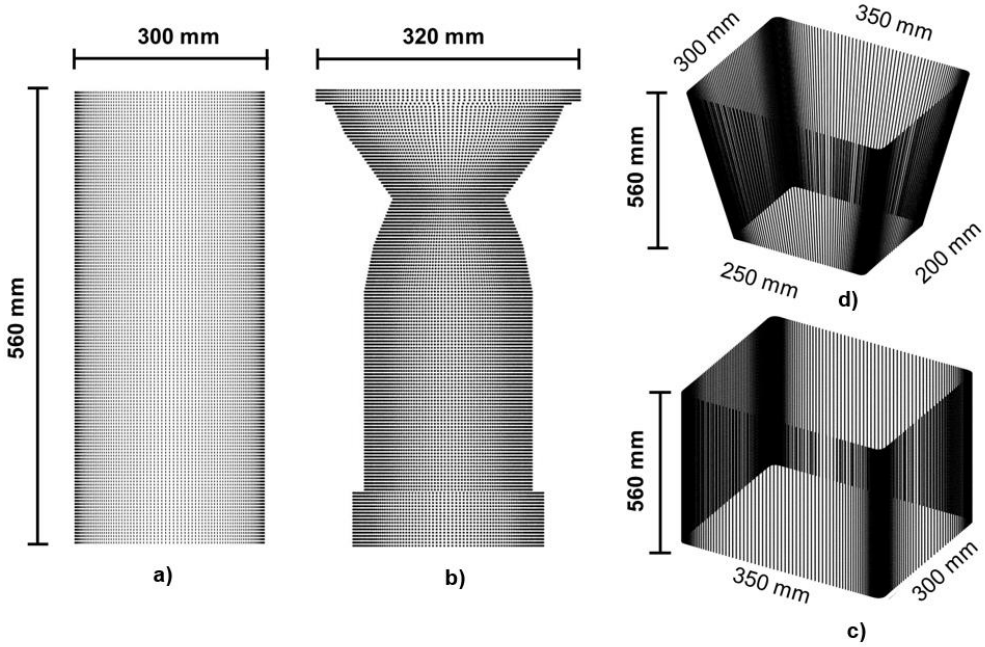


Fig. 9 The four different braiding core shapes studied

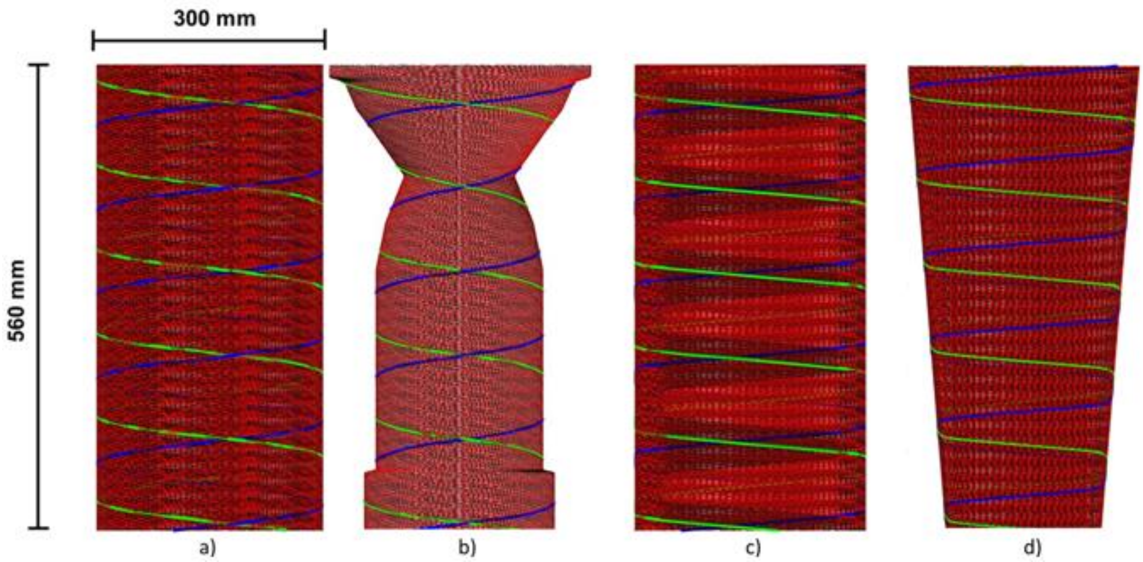


Fig. 10 Fiber paths for each braiding core

The analytical solution is determined by the Rosenbaum's equation written below.

$$CF = 1 - \left(1 - \frac{w_{yarn} N_{bob}}{2\pi D \cos\alpha}\right)$$

With,

- CF: the cover factor, e.g. $CF = 1$ the under layer is fully covered
- w_{yarn} : the width of the carbon fiber [mm]
- N_{bob}: the number of bobbins
- D : the diameter of the braiding core [mm]
- α : the fiber angle [°]

The following figure shows the comparison between the kinematic solution (the process's model output) and the analytical solution.

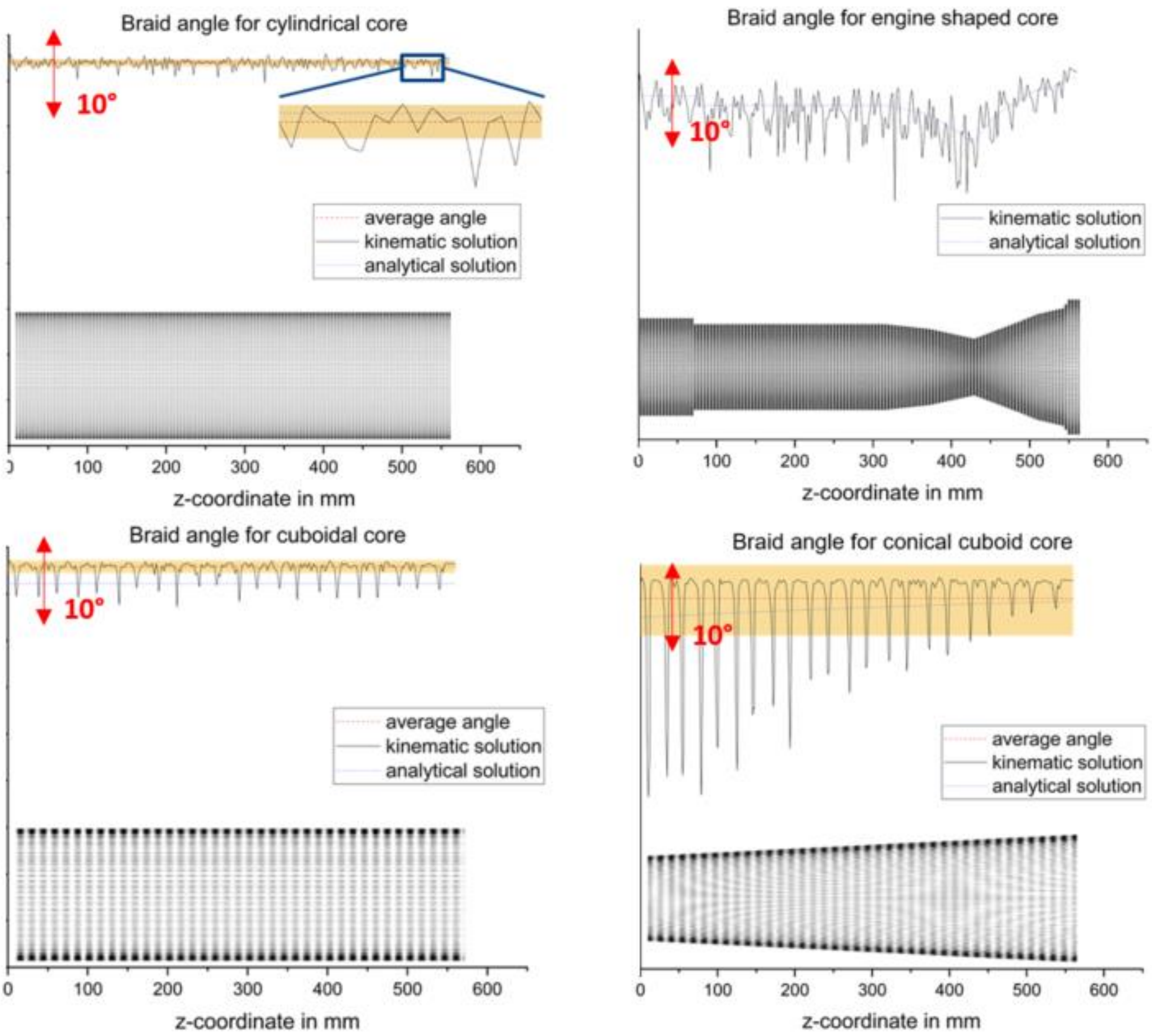


Fig. 11 Overview of results for each braiding core shape

For the most "simple" shapes (cylindrical and cuboidal), the kinematic solution is quite close to the analytical solution. The noise, or deviations, from the analytical solution can be reduced by refining the mesh of the braiding core model. However, for more complex shapes such as "nozzle" shapes or conical cuboid shapes the kinematic solution is quite different from the analytical solution.

A second approach is based on optical analysis. The optical analysis consists in a direct image analysis on the braided structure. The angle fiber is measured on the component using a polarization camera, a lens and a ring light (**Fig. 12**).

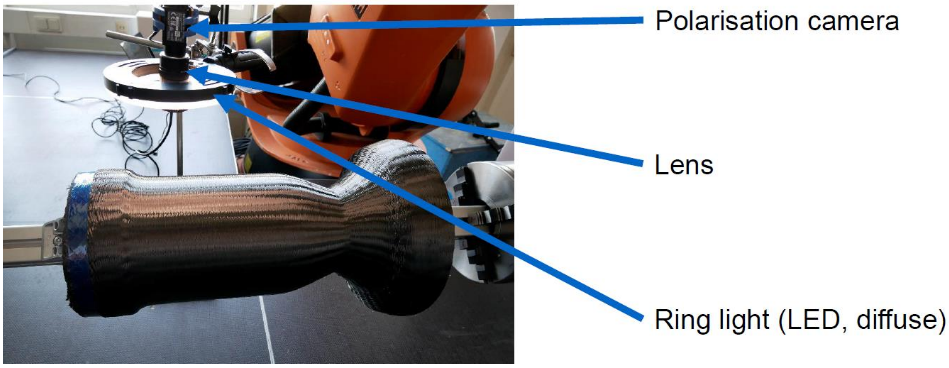


Fig. 12 Optical analysis setup

The analysis gives the fiber angle at every single location on the component, as shown in **Fig. 13**.

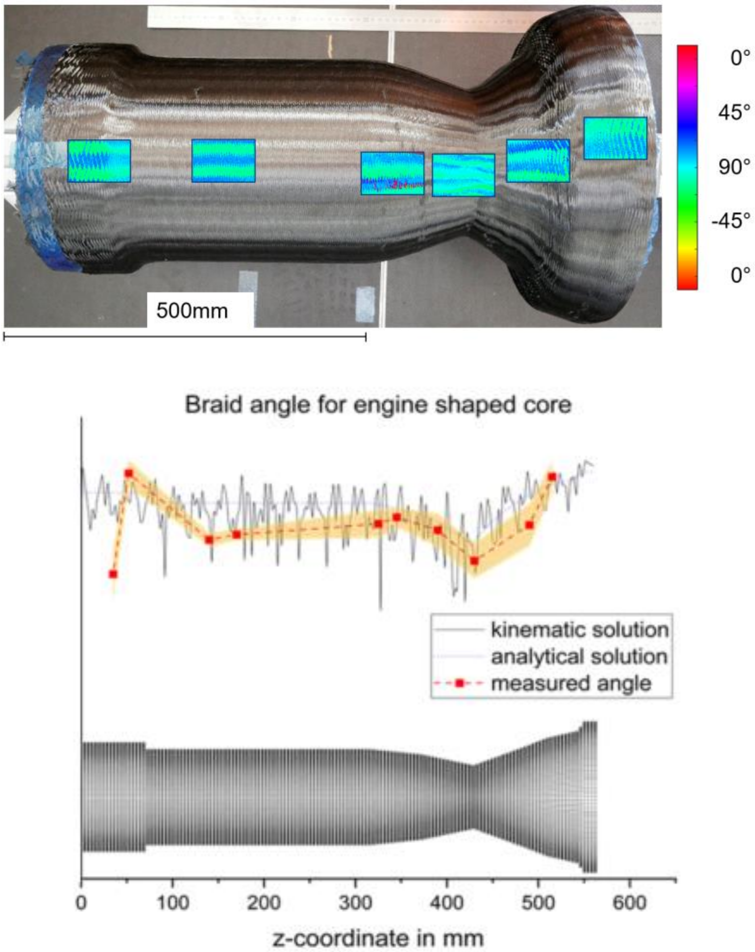


Fig. 13 Optical analysis results for the "nozzle" shape

As shown in Fig. 13, the measured angle corresponds quite well with the kinematic solution given by the "Process Model".

3. Mechanical Characterization of CARBOTEX®

As for any other material, prior to use CARBOTEX® in designing operational systems, it is essential to characterize each physical properties of CARBOTEX®.

As explained above, when it comes to simulate the mechanical behavior of the dual-mode ramjets under thermo-mechanical loads, a macro-scale approach is used for a better compromise between accuracy and time-consuming computations.

CARBOTEX® is a highly orthotropic material, meaning it is necessary to characterize each of its characteristics in each direction of space. The mechanical tests on samples are composed of: tensile tests, bending tests, compression tests, iosipescu shear tests, bearing tests, compression tests and interlaminar-shear tests. The following paragraph focuses on the tensile tests in the "weak" and "strong" mechanical directions of the engine.

The following paragraphs use the "Braid-Longi" architecture as a working example. The complex structure of this architecture can be depicted into three different CMC along its thickness:

- Braid-Longi + SiC (BL+SiC) also called "cold gas wall", that part of CARBOTEX® is not exposed to the extreme temperatures (>2000K) of the combustion chamber ;
- Braid-Longi with "textile reinforcements" (BLI) corresponds to the "core" of CARBOTEX®, that part can be exposed to the fuel in the case of a fuel-cooled structure made in CARBOTEX® for its own cooling ;
- Braid-Longi with "textile reinforcements" + SiC (BLI+SiC) also called "hot gas wall", that part of CARBOTEX® is exposed to the extreme temperatures of the combustion chamber.

Before and after each mechanical test a computer tomography (CT) evaluation is performed in order to detect cracks and other features that can be observed inside CARBOTEX® samples. A strain measurement is also put in place by means of a digital correlation system (ARAMIS 12M).

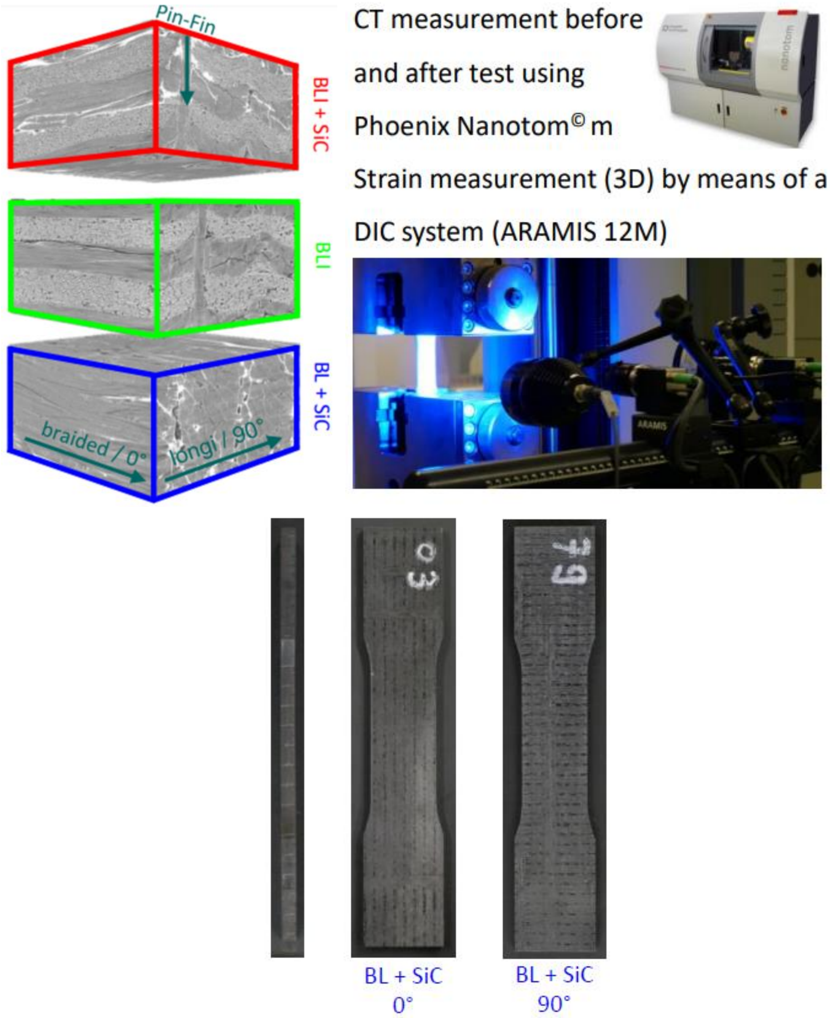


Fig. 14 The three different states of CARBOTEX® (left), the CT measurement device (top center), the ARAMIS 12M system (bottom center) and tensile samples (right)

The Fig. 15 shows how the presence of longitudinal fibers, SiC layer and inlays influence the mechanical behavior of CARBOTEX® in tensile.

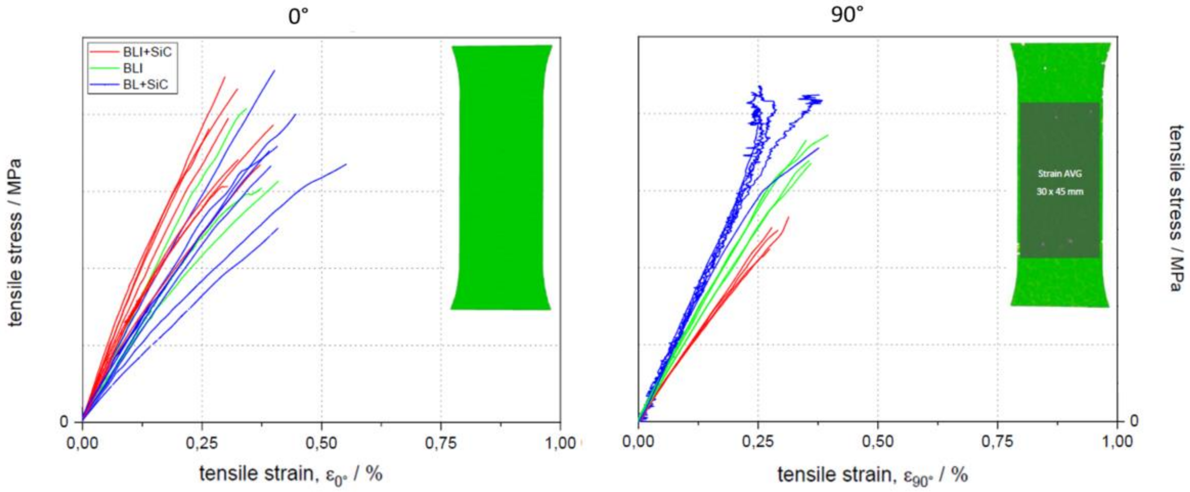


Fig. 15 Tensile tests results on BL+SiC in the 0° (left) and 90° (right) direction

The right picture (tensile tests in the 90° direction) clearly shows that:

- The high amount of braided fibers in the 90° direction, coated with a SiC layer, increases the tensile strength of the sample and tends to increase the Young Modulus as well, e.g. the material gets more brittle (blue curve – BL +SiC) ;
- The presence of "textile reinforcements" decreases the fiber volume in the 90°, therefore tends to decrease the tensile strength of the material (green curve – BLI) ;
- The infiltration of SiC in the material associated with "textile reinforcements" creates inner brittle layers that significantly decreases the tensile strength of CARBOTEX® (red curve – BLI + SiC).

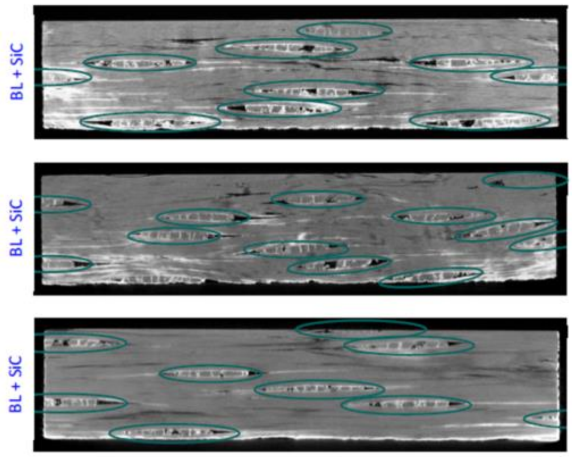
On the other hand, in the 0° direction (left picture), the trend is different the left picture:

- The "textile reinforcements" associated with a SiC infiltration increases significantly the tensile strength of the material by adding more fibers carrying the load (red curve – BLI + SiC) ;
- The absence of "textile reinforcements" in the 0° direction shows a decrease of the tensile strength explained by a lack of fibers being able to carry the mechanical load (blue curve – BL +SiC and green curve – BLI).

Finally, as the textile architecture of CARBOTEX® is strongly oriented along the 90° axis (Fig. 4), the standard deviation from the mechanical tests along the 0° axis is quite large:

- STD ~ 30% for the tensile strength in the 0° direction (Fig. 15) ;
- STD ~ 7% for the tensile strength in the 90° direction (Fig. 15).

Therefore, it is necessary to normalize the results with respect to the number of longitudinal fibers. The Fig. 16 shows the number of longitudinal fibers for each kind of sample enabling to determine the average normalized strength for BLI+SiC, BLI and BL+SiC. By counting the longitudinal fibers for each sample, the STD can be significantly reduced.



structure	normalized strength MPa/#	rel. STD orig. strength %	rel. STD norm. strength %	state
BLI+SiC	REF +54%	12	4	longi fibers + inlays + siliconization
BLI	REF +12%	20	5	longi fibers + inlays
BL+SiC	REF	17	2	only longi fibers + siliconization

Fig. 16 Number of longitudinal fibers per sample and normalized results

Thus, the following conclusions can be drawn:

- The number of longitudinal fibers determine the tensile strength (blue curve – BL+SiC) ;
- The addition of inlays tends to increase the tensile strength of the sample since the inlays increase the fiber volume content in the load direction (green curve – BLI) ;
- Contrarily to the 90° samples, the SiC layer impregnating the inlays increase significantly the tensile strength of the sample (red curve – BLI+SiC)

4. Conclusions

This paper gives a short overview of the recent studies that have been led on CARBOTEX® over the last five years. It is explained how the manufacturing process of CARBOTEX® can be adapted depending on the needs when designing a high-velocity air breathing propulsion system.

Furthermore, the braiding process of CARBOTEX® was modelled to determine accurately the fiber paths and the fiber angles on different geometries used on dual-mode ramjet, scramjet or high speed vehicle airframe. The output of this "process model" is being used as an input for a 3D "geometrical model".

Finally, the influence of different structural properties on the mechanical behavior for a chosen textile architecture has been investigated:

- A correlation between tensile strength and the number of longitudinal fibers per cross section has been identified.
- In contrast, better mechanical values have been measured along other directions for structures containing only braided fibers and siliconization.

5. References

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