MODELLING THE MECHANICAL PROPERTIES OF SIC$_F$/SIC BRAIDED COMPOSITE TUBES

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Abstract

The aim of this paper is to present the first steps of multiscale modelling for braided SiC$_f$/SiC composite tubes. A large characterization campaign is needed to provide data on the composite behaviour. For this purpose, a tensile test and an internal pressure test dedicated to the tubular geometry have been developed. Results show a reproducible and typical mechanical behaviour of ceramic composite materials. Finally, the geometrical modelling of the braided preform is introduced.

1 Introduction

Thermostructural composites such as ceramic matrix composites (CMC) are more and more used in the industry. The French Alternative and Atomic Energy Comission (CEA) is designing the IVth generation of nuclear reactors and several geometries have been proposed to confine fissionable material including the tubular shape. Good properties of silicon carbide (SiC) based composites such as transparency for fast neutrons and high thermomechanical properties make them potential candidates for cladding material. These structures are relatively new and their mechanical properties are poorly known. The aim of this study is to develop a model of mechanical properties of braided SiC/SiC tubes in order to size up such structures. In addition, this work is part of a "virtual material" process based on a multiscale approach and represents the first step in achieving a complete numerical model of composite tubes.

Main dimensioning stresses under operative conditions are the internal pressure and traction whereas during handling, the dimensioning stress is bending. A complete experimental procedure has been developed to test 3D braided tubes in tensile load and internal pressure load. Meanwhile, a geometrical model of 3D braided preform has been built using specific tools developed for modelling woven composites.

2 Mechanical characterizations

2.1 As received material

Studied tubes have an interlock fibre structure: yarns switch from one layer to another in order to avoid delamination issues. These yarns contain about 500 Hi-Nicalon type-S fibres which have a modulus of 375 GPa and a Poisson coefficient of 0.15 [1]. Fibres are transversely isotropic. Matrix and pyrocarbon interphase are added using a chemical vapour infiltration technique. The matrix has a modulus of 400 GPa and a Poisson coefficient of 0.2 [1]. The interphase is included to act like crack deflector at the fibre/matrix interface. Yarns are braided with an angle of 30° between their direction and the axe of revolution of the tube.

Once densified, the internal and external diameters of the tubes are respectively 7.9 mm and between 9.5 and 9.9 mm which represent a thickness of 0.8 to 1 mm. With analyses on micrograph images, volume fraction of fibres, matrix and porosity in yarns have been measured as 58% of fibre, 35% of matrix and 7% of porosity (fig. 1).

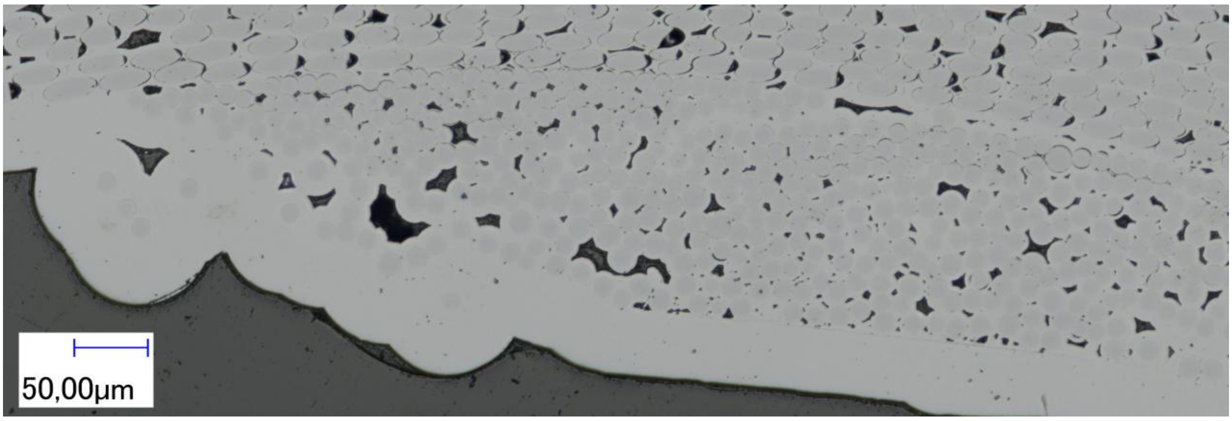


Figure 1. Micrograph image of a yarn section of a SiC_f/SiC braided tube.

Plates with the same type of reinforcement have also been elaborated. They are obtained by cutting a tubular dried preform which is densified on a flat surface while the angle between yarns direction is maintained.

2.2 Experimental procedure

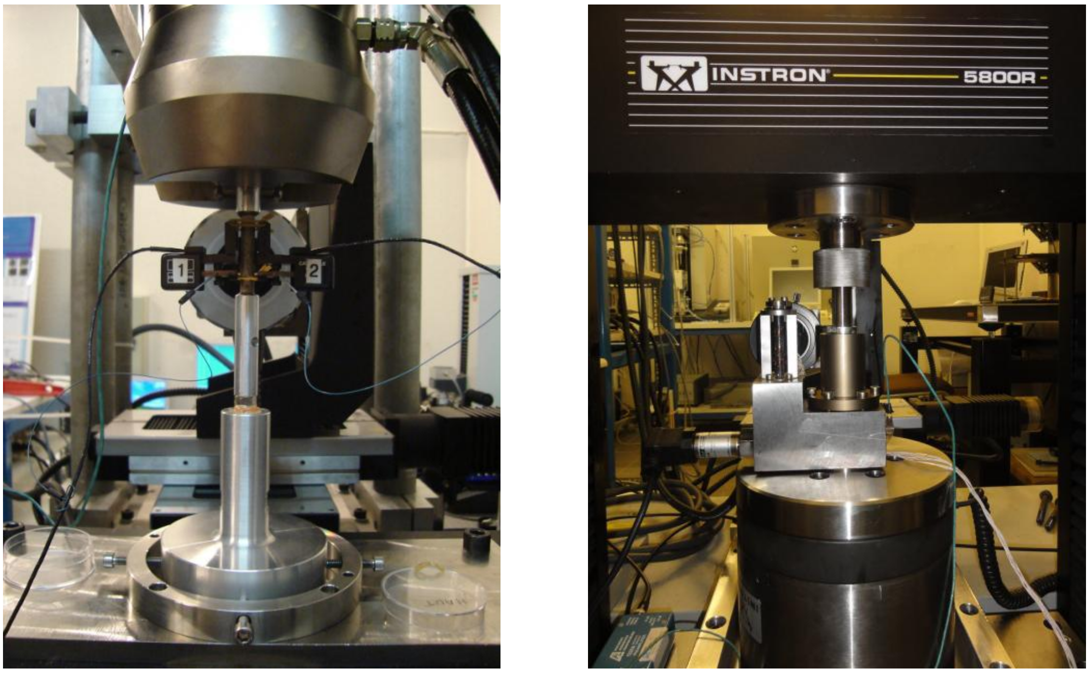
2.2.1 Tensile test

The test machine is a 100 kN Instron 4505 loading frame. All tensile tests use a 20 kN load-cell and are displacement controlled. The loading rate is 0.05 mm/min.

Before doing the test, material has to be prepared properly in order to avoid damages from hydraulic grips. For this purpose, tubes are bonded to aluminium pieces with a structural glue. Then, the upper part is fixed in a grip while the lower part is bonded to another aluminium piece which is maintained on the cross-head (fig. 2a). This system allows proper alignment between the machine and the tube to avoid bending. Plate samples are simplest than tubes to prepare. Aluminium tabs are glued on each end of the tensile specimen. Then, both sides are fixed in grips. For this kind of tests, tubes are 60 to 70 mm long and plate samples are 120 mm long.

In order to measure strain, two contacting extensometer with 25 mm gauges are placed in front of each other on tubes (fig. 2a). Moreover, digital image correlation (DIC) is used to measure displacement and strain field on the surface of the tested tube. A Hamamatsu c4742-95 camera recorded one frame per second with a 1280x1024 12 bits resolution.

Stresses are calculated using a section measured by optical profilometry. Internal diameter is set to 7.9 mm while external diameter is taken as the largest profilometric measure.



(a) (b)

Figure 2. (a) Photographs of tensile test machine and (b) internal pressure machine.

2.2.2 Internal pressure test

The internal pressure device has been developed in collaboration with the CEA (Marcoule, DEN/DTEC). To impose pressure, oil is injected in an elastomeric pipe which is inserted into the tested tube (fig. 2b). Metallic parts of 0.4 mm height are used to maintain tubes on a unique axe but the edges of the tube remain free to move vertically. A pressure transducer (maximum pressure 1000 bars) is set on the side of the device and a 100 kN load-cell is positioned under the device.

With such a device, it is difficult to use a contacting extensometer. Thereby, for all internal pressure tests, only DIC and strain gauges (CEA-06-375UW-350) are employed. The camera records one frame per second. The area of the strain gauges grid is 9.53x4.57 mm².

Circumferential stresses are calculated using a formula derived from the mechanical balance equation of a tube. This formula links the circumferential stresses ($\sigma_{\theta\theta}$) to the internal and external pressure (P_{int} and P_{ext}), the internal and external radius (R_{int} and R_{ext}) and the radius (r) with

$$\sigma_{\theta\theta}(r) = \frac{P_{\text{int}} R_{\text{int}}^2 (r^2 + R_{ext}^2)}{(R_{ext}^2 - R_{\text{int}}^2) r^2} - \frac{P_{ext} R_{ext}^2 (r^2 + R_{\text{int}}^2)}{(R_{ext}^2 - R_{\text{int}}^2) r^2} \qquad (1)$$

During an internal pressure test, external pressure is the atmospheric pressure and is negligible compared to the internal pressure. So the term involving P_{ext} is neglected. To determine stresses on the external surface of the tubes, (1) is used with $r = R_{ext}$. This formula (2) is called "the external radius approximation" [2]. Another adaptation with $r = R_{\text{int}}$ is used to determine stresses on the internal surface of tubes so that:

$$\sigma_{\theta\theta}(R_{ext}) = 2\frac{P_{\text{int}}R_{\text{int}}^2}{R_{ext}^2 - R_{\text{int}}^2} \qquad \sigma_{\theta\theta}(R_{\text{int}}) = P_{\text{int}}\frac{R_{ext}^2 + R_{\text{int}}^2}{R_{ext}^2 - R_{\text{int}}^2} \tag{2}$$

2.3 Results

CMC braided tubes have an elastic modulus about 180 GPa and a Poisson coefficient between 0.2 and 0.3. The tensile response of the CMC braided tubes is plotted in Fig 3. The loading/unloading behaviour is typical of SiC_f/SiC composites with small residual strains which result from thermal residual stresses after elaboration at high temperature.

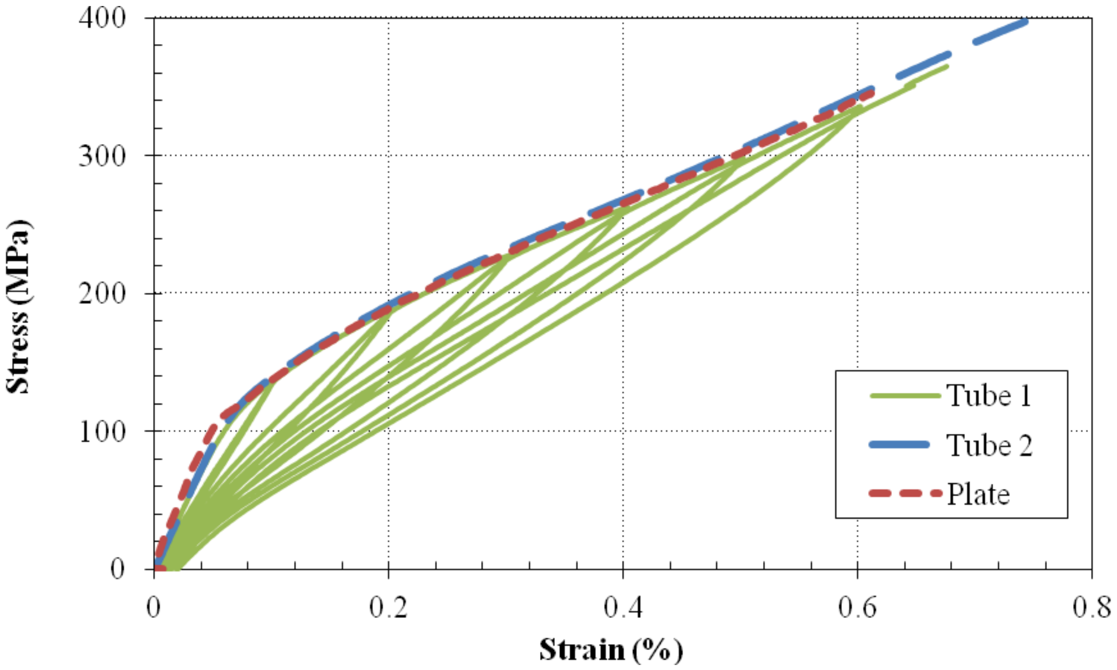


Figure 3. Monotonic and cyclic behaviour of the SiC_f/SiC braided tubes and plates in tensile loading.

Mechanical behaviour of plates in tensile loading reveals similar to mechanical behaviour of tubes. This confirmation allows considering high temperature tensile tests using plates rather than using tubes.

Damage characterization is required to understand 3D braided tubes mechanical behaviour. The damage mechanisms in CMC materials are well described in previous studies [3-4]. First, matrix begins to crack and those micro-cracks are normal to the loading direction. Second, these micro-cracks spread along yarns. Finally, yarns fracture and lead to the ruin of the material.

A 2D braided tube has been tested under internal pressure. This tube has a balanced texture which allows assuming that its behaviour under tensile loading will be similar to its behaviour under internal pressure. This 2D braided tube has an internal diameter of 6.85 mm for an external diameter of 8.80 mm with an angle between yarn directions of 45°.

As expected, the mechanical response of the tube under internal pressure is similar to the behaviour in tensile loading (fig. 5). Mechanical properties are reported in table 1.

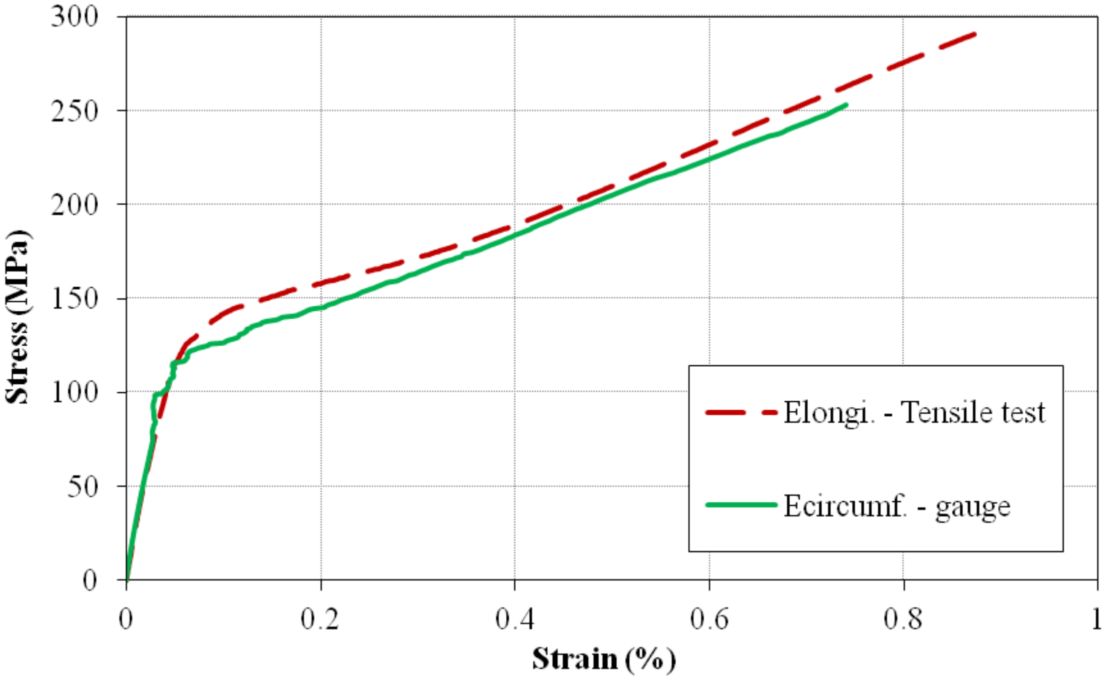


Figure 5. Monotonic strain/stress response of a 2D SiC$_f$/SiC braided tube tested under internal pressure load. The tensile response is also plotted.

Tube	P_m (bars)	$\sigma_{\theta\theta}^{m} f_{ext}$ (MPa)	$\sigma_{\theta\theta}^{m} f_{\text{int}}$ (MPa)	E (GPa)	$\varepsilon_{\theta\theta}^{m}$ (%)
2D tube	823	271	335	293 ± 9	0.75 ± 0.02

Table 1. Main mechanical properties obtained from internal pressure test (maximum pressure P_m , maximum orthoradial stress on the external surface $\sigma_{\theta\theta}^{m} f_{ext}$ and on the internal surface $\sigma_{\theta\theta}^{m} f_{\text{int}}$, the longitudinal modulus E and the ultimate strains $\varepsilon_{\theta\theta}^{m}$).

3 Multiscale modelling

The multiscale approach includes two successive steps at the micro scale (homogenization of a yarn) and the meso scale (homogenization of an infiltrated preform). Several geometrical modelling tools have been developed in a previous study [5]. A specific tool has been improved to model 3D interlock braided tubes using a geometrical analogy between plates and tubes [6]. In addition, a numerical relaxation method has been incorporated in the modelling process. This approach is designed to simulate the tension during braiding and add realism to the modelled preform (fig. 6).

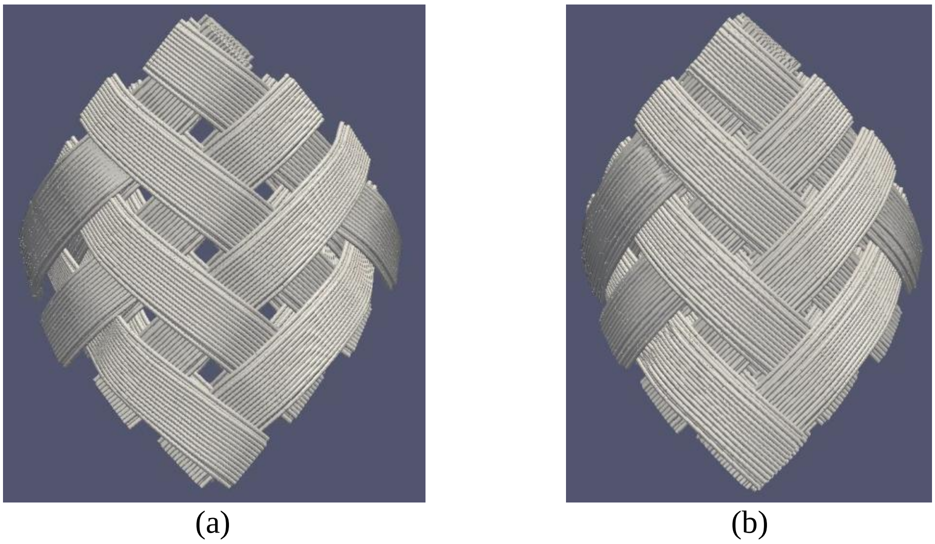

(a) (b)

Figure 6. Modelling the dried preform of a 2D braided tube. (a) Before relaxation and (b) after relaxation.

At this moment, only a dried preform is modelled. In order to achieve the geometrical modelling of 3D braided tubes, matrix and interphase have to be added. Working on 3D images of dried preform will simplify the addition of the matrix phase. Dried preform image can be dilated until the matrix thickness is reached.

Once a complete image of 3D braided tubes is generated, a voxel finite element method will allow meshing it. Then a comparison between numerical and experimental behaviour of 3D braided tubes will be possible in the linear domain. Damage mechanisms will be added in a next step.

4 Conclusion

A mechanical characterization has been conducted on 3D SiC_f/SiC braided tubes. Experimental results reveal a typical damageable behaviour. When elaborated with the same texture than tubes, plates have a mechanical response similar those of tubes. The internal pressure test has been validated and 3D braided tubes will be tested soon. A complete geometrical model of dried preform has been developed. With the use of a relaxation method, preforms are more realistic. Matrix part will be added soon and comparison with experimental results for the linear elasticity will be allowed thanks to a voxel finite element method.

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