ORAL POSTER REFERENCE : ICF100966OR

DAMAGE AND ULTIMATE FAILURE OF TEXTILE CERAMIC MATRIX COMPOSITES

J. Lamon

Laboratoire des Composites Thermostructuraux
UMR 5801 (CNRS-SNECMA-CEA-UB1)
3, Allée de la Boétie, 33600 Pessac, France

ABSTRACT

Composites are heterogeneous materials. Brittle matrix composites combine brittle constituents. As a consequence, damage and failure exhibit typical features that influence the response under load. A large amount of data on the mechanical behavior of unidirectionnally reinforced ceramic matrix composites can be found in the literature. The present paper examines the ultimate failure and damage mechanisms in 2D woven SiC/SiC composites. The failure mechanisms as well as features of ultimate failure are addressed. In particular, it is emphasized that ultimate failure and matrix damage are successive and separate phenomena and that the statistical distribution of strength data exhibit a limited scatter and a very limited dependence on the stressed volume.

KEYWORDS

Ceramic-matrix composites, fracture, interface, non-linear behavior, probabilistic methods.

INTRODUCTION

The concept of composite materials is very interesting. It covers a wide variety of materials of which one can tailor the properties with respect to end use applications, by playing with the combination of constituents. A large variety of respective properties and arrangement can be devised.
Models of the mechanical behavior are required to design either structures or materials. Those approaches aimed at predicting the stress-strain behavior from constituent properties are based on micromechanics (see for instance [1-2]). They are essentially appropriate for material design purposes. Those aimed at designing structures are based on continuum damage mechanics. The composite is considered to be a continuous medium (or an homogeneous material) at macroscopic or an intermediate mesoscopic scale (see for instance [3]).
The mechanical behavior of ceramic matrix composites displays several typical features that differentiate them from the other materials, including the other classes of composites as well

as homogeneous (monolithic) materials. With a view to developing appropriate models, it is required that the basic phenomena that determine composite mechanical behavior be well understood and properly described. A lot of papers have been devoted to unidirectionnally reinforced composites. The mechanical behavior is essentially *damage sensitive.* It consists in a non-linear response as a result of transverse cracking in the matrix. Cracks are arrested by fibers and they are deflected at fiber/matrix interfaces causing fiber debonding. Ultimate failure is dictated by fibers. Matrix cracking and fiber failure are random brittle failure phenomena, as a result of the presence of populations of fracture-inducing flaws distributed randomly [1, 2, 4, 5].

In those textile composites (i.e. those composites reinforced with fabrics of fiber bundles), damage and ultimate failure are influenced by microstructure [6, 7]. The 2D SiC/SiC composites manufactured by Chemical Vapor Infiltration provide an excellent illustration of these effects. Their microstructure is highly heterogeneous, as a result of the presence of woven infiltrated tows that behave as physical entities, large pores (referred to as macropores) located between the plies or at yarn intersections within the plies and a uniform layer of matrix over the fiber preform (referred to as the intertow matrix). Much smaller pores are also present within the tows. Extensive inspection of these composites under tensile loads using a microscope, and acoustic emission recording allowed damage and failure mechanisms to be identified [7, 8].

The paper discusses typical features of damage and ultimate failure and in a textile ceramic matrix composite (2D SiC/SiC).

DAMAGE IN 2 D WOVEN SiC/SiC COMPOSITES

Damage in 2D woven SiC/SiC consists essentially in transverse cracks in the matrix and associated interface cracks resulting from deviation of the matrix cracks by the tows and the fibers within the tows (also referred to as debonding). Three main steps can be distinguished during tensile tests under incremental loads, using a microscope mounted on the testing machine (figure 1) [7] :
Step 1: cracks initiate first in the intertow matrix at macropores where stress concentrations exist (strains between 0.025 % and 0.12 %).
Step 2: cracks appear then in the transverse tows (strains between 0.12 % and 0.2 %).
Step 3: transverse microcracks initiate in the longitudinal tows for strains larger than 0.2 %. These microcracks remain localized within the longitudinal tows. They do not propagate within the rest of the composite. The matrix in the longitudinal tows experiences a fragmentation process and the crack spacing decreases as the load increases.
For both first families of cracks deflection occurs at the periphery of longitudinal tows, whereas for the third family of cracks it occurs at the fiber/matrix interfaces within the tows [7, 9].
The significant Young's modulus decreases that are generally observed during tensile tests [7, 9] (figure 2) illustrate the dependence of damage on the heterogeneous microstructure of composite. Young's modulus refers to the tangent modulus determined from the linear portion of the reloading curve obtained on unloading-reloading cycles. The major modulus loss (70 %) is caused by both the first families of cracks (strains < 0.2 %). Microcracks within the longitudinal tows are responsible for only a 10 % loss. The 70 % modulus loss reflects big changes in load sharing: the load becomes carried essentially by matrix infiltrated longitudinal tows (tow overloading). During microcracking in the longitudinal tows, load sharing is affected further, and the load becomes carried essentially by the fibers within the

tows (fiber overloading). The elastic modulus reaches a minimum value described by the following equation :

$$E_{min} = \frac{1}{2} E_f V_f \quad (1)$$

Eqn. (1) implies that the matrix contribution in load carrying is negligible. At this stage matrix damage and debonding are complete. Saturation of matrix cracking is generally observed for a 0.8% strain. At this stage, fibers are fully loaded. The mechanical behavior is controlled now by the fiber tows oriented in the direction of loading.

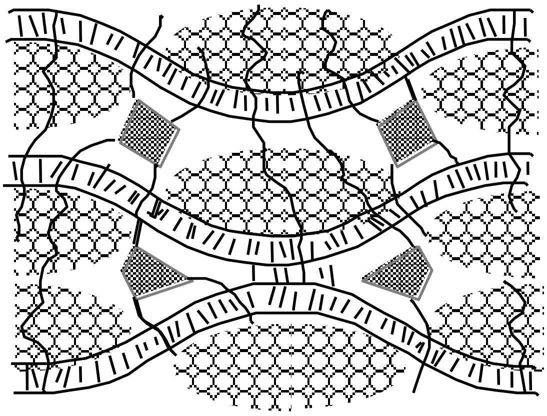

Figure 1 : Schematic diagram showing microstructure and matrix cracking in a 2D SiC/SiC composite during a tensile test (longitudinal strain = 0.8 %)

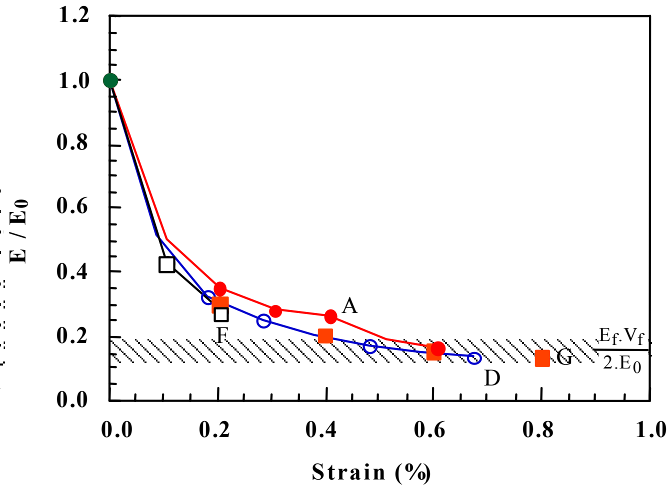

Figure 2 : Relative elastic modulus versus applied strain during tensile tests on various 2D woven SiC/SiC composites reinforced with treated fibers : (A) Nicalon/$(PyC_{20}/SiC_{50})_{10}$/SiC, (D) Nicalon/PyC_{100}/SiC, (F) Hi-Nicalon/PyC_{100}/SiC, (G) Hi-Nicalon/ $(PyC_{20}/SiC_{50})_{10}$/SiC

ULTIMATE FAILURE

Failure mechanisms

Under a tensile load, ultimate failure of a tow of parallel fibers involves two steps [10, 11]:
- a first step of stable failure,
- a second step of unstable failure.

During the first step, fibers fail individually as the load increases. The applied load is carried by the surviving fibers only. In the absence of fiber interactions, there is no load transfer from the surviving fibers to the broken fibers. The load on the surviving fibers increases when a fiber fails. The load that was carried by the broken fibers is shared by the surviving ones (global load sharing).

The unstable failure (second step) occurs when the surviving fibers cannot tolerate the load increment resulting from a fiber failure. At this stage, a critical number of fibers have been broken.

Ultimate failure of matrix infiltrated tows also involves a two-step mechanism and a global load sharing when a fiber fails [1, 12]. In the presence of multiple cracks across the matrix and the associated interfacial debonds, the load carrying capacity of the matrix is tremendously reduced or annihilated. The load is taken up equally by the remaining intact fibers, and the fibers fail only once [1, 12]. The matrix infiltrated tows can be assimilated to bundles of fibers subject to the specific stress field induced by the presence of multiple cracks across the matrix. Ultimate failure occurs when a critical number of fibers have failed.

This mechanism also dictates ultimate failure in textile ceramic matrix composites. Ultimate failure is caused by the failure of a critical number of broken tows (≥ 1).

This mechanism is at variance with that observed in polymer matrix impregnated tows, where a local load sharing occurs when a fiber fails [4]. In these composites, the fibers fail first. Therefore, the uncracked matrix is able to transfer the load to the broken fibers.

Features of ultimate failure

In SiC/SiC composites, ultimate failure generally occurs after matrix cracking saturation. The fibers break under loads close to the maximum at ultimate failure [2, 7, 9]. Matrix damage and ultimate failure thus appear to be successive and separate phenomena. They may be regarded as independent phenomena when one considers that the load is carried by the fibers and there is no contribution of the matrix during fiber failures. They may be also regarded as dependent when one considers that the stress-state that operates on the fibers at ultimate failure results from matrix cracking. Both viewpoints can be accounted for in micromechanics- based models.

Ultimate failure is highly influenced by stochastic features. Since fibers are brittle, they are highly sensitive to the presence of flaws (stress concentrators), that are distributed randomly. As a consequence, the strength data exhibit a significant scatter, as illustrated by figure 3 [13]. Figure 3 shows the relationship between various sets of strength data measured respectively on single fibers, tows, matrix infiltrated tows and textile composites. It can be noticed that the strength magnitude and the strength interval decrease when considering successively single fibers, tows, matrix infiltrated tows and textile composites. As a result of the previously mentioned two step mechanism, the ultimate failure becomes dictated by the lowest strength extreme of the distributions, i.e. the lowest strength extreme of the distribution of fiber strengths for the failure of tows and infiltrated tows, and that of infiltrated tow strengths for the 2D composites failure. These strength extremes correspond respectively to the critical number of individual fiber breaks ($\approx$ 17% for SiC Nicalon fibers [1]) and to the critical number of tow failures (≥ 1). The gap between the respective magnitudes of the strengths pertinent to the tows and to the matrix infiltrated tows results from the method of strength determination. The critical number of individual fiber breaks was taken into account in the tow strength only. The strength of the infiltrated tows and the textile composites was derived from the area of the cross section of specimens.

Figure 4 illustrates the scatter in strengths observed on 2D woven SiC/SiC composites tested under tensile loading conditions [14]. The specimens were loaded parallel to a tow direction. Tests were performed on two batches of 12 dog-bone shaped-specimens each, including small and large specimens. The statistical distributions of strength data were determined using ranking statistics. Ordering the strengths from smallest to largest and assigning a ranking number i, the probabilities of failure were then assigned by the following relationship :

$$P(\sigma_i) = (i-0.5)/N \tag{2}$$

where N is the sample size.

The scatter in ultimate strengths can be characterized using the Weibull modulus m. Assuming that the stress-state is uniform :

$$P(\sigma) = 1 - \exp (V/V_0)(\sigma/\sigma_0)^m \qquad (3)$$

Where V is the stressed volume, $V_0 = 1mm^3$, σ is the applied stress and σ_0 is a scale factor.
The estimates of m obtained using the maximum likelihood method are rather high: m = 17 for the smaller specimens, and m = 20 for the larger ones.
Figure 4 also shows that the strength data exhibit a very limited dependence on the stressed volume. It can be noticed that, at low stresses, the higher strengths were obtained for the larger volumes.
Assuming that the tensile strengths of the composite follow weakest-link scaling, the ultimate strengths of the large specimens were predicted from the failure data of the small specimens, using the following equation derived from (1):

$$\sigma_1/\sigma_2 = (V_2/V_1)^m \qquad (4)$$

where $\sigma_1(P,V_1)$ and $\sigma_2(P,V_2)$ are ultimate strengths for a given failure probability P and for stressed volumes V_1 and V_2.
Figure 4 shows that the calculated strengths for the large specimens are underestimated significantly. The Weibull model thus predicts a great scale effect which is at variance with the trend shown by experimental results. This indicates that the Weibull approach is not appropriate to the description of ultimate failure of brittle matrix composites.

According to the Weibull predictions, a significantly larger size effect would be observed on an equivalent monolithic material. This result as well as the fiber-composite relations depicted on figure 3 suggest that the flaw sensitivity was tremendously reduced in the 2D SiC/SiC composite, as a result of the damage mechanism and the individual failure breaks that cause a truncating of the populations of pre-existing flaws. Those flaws that become responsible for ultimate failure are located in the previously mentioned critical fibers of which failure leads to catastrophic failure of composites [1, 14].

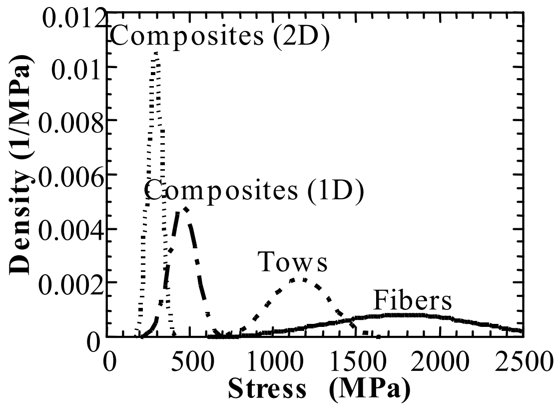

Figure 3 : Strength density functions for SiC fibers (NLM 202), SiC fiber tows, SiC/SiC (1D) minicomposites and 2D SiC/SiC composites.

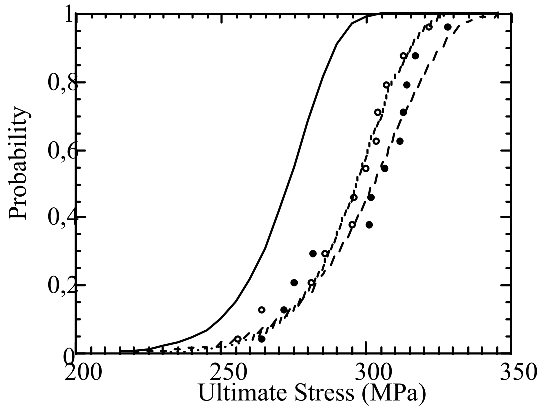

Figure 4 : Scale effects in 2D woven SiC/SiC composites. Influence of specimen dimensions on ultimate failure in tension : (•) $V_1 = 8 \times 30 \times 3$ mm^3, (o) $V_2 = 160 \times 120 \times 3$ mm^3, solid line : prediction of failure of larger specimens (volume V_2) using the Weibull's model.

Conclusions

In 2D woven SiC/SiC composites, ultimate failure generally occurs after matrix cracking saturation, under longitudinal strain ≥ 0.8%. Matrix damage and ultimate failure thus appear to be successive and separate phenomena. However under incremental loading, the load becomes progressively carried by the fibers only after matrix cracking saturation. Ultimate failure becomes controlled by the longitudinal tows. Fiber breaks initiate under high loads close to ultimate failure. Ultimate failure exhibits several interesting features including a small scatter in strength data and a very limited dependence on the stressed volume. These features can be related to the failure mechanisms that involve tow failures. They indicate a limited sensitivity to the flaw populations.

6- Acknowledgements

The author gratefully acknowledges support of SNECMA and CNRS through grants obtained by the Ph.D students involved in the generation of the results reported here (Ph. Forio, V. Calard, N. Lissart, L. Guillaumat). J. Forget and C. Dupouy are also acknowledged for their assistance with manuscript preparation.

7- References

1. N. Lissart and Lamon J. (1997) *Acta Mater*. 45, 1025.
2. Curtin W.A. (1991) *J. Am. Ceram. Soc*. 74, 2837.
3. Ladevèze P. (1992) *J. Computers and Structures*. 44, 79.
4. Batdorf S.B. (1985) in Probabilistic methods in the mechanics of solids and structures: Proc. IUTAM Symposium, Springer-Verlag. p. 299-305.
5. Sutcu M. (1989) *Acta Metal*. 37, 2567.
6. Karandikar P., Chou T.W. (1993). *Composites Science and Technology*, 46, 253.
7. Guillaumat L. and Lamon J. (1999) *Revue des Composites et des Matériaux Avancés*. 9, 183.
8. Forio Ph., Lamon J. (1999) in : Proc. The Twelfth International Conference on Composite Materials (ICCM 12), CD-ROM, Paris, France.
9. Forio Ph.(2000) *PhD Thesis*, University of Bordeaux, France.
10. Daniels H. E. (1944) *Proc. Roy. Soc. London*. 183, 405.
11. Coleman B. D. (1958) *J. Mech. Phys. Solids*. 7, 60.
12. Cao H., Thouless M.D. (1990) *J. Am. Ceram. Soc*. 73, 2091.
13. Calard V. (1998) *PhD Thesis*, University of Bordeaux, France.
14. Calard V. and Lamon J. (2001) to be published.