

CHARACTERIZATION AND MODELLING OF CERAMIC MATRIX COMPOSITES SUBMITTED TO SEVERE THERMO-MECHANICAL LOADING

Frédéric Laurin[1], Yelitza Delgado González[2], Stefan Reh[3], Angela Russo[4], Charles Footer[5], Florence Roudolff [1]

[1]DMAS, ONERA, University Paris-Saclay, 92320, Châtillon, France
[2]Nederlands Lucht- en Ruimtevaartcentrum NLR (Netherlands Aerospace Centre)
[3]Deutsches Zentrum für Luft- und Raumfahrt DLR (German Aerospace Center)
[4]Università degli Studi della Campania "Luigi Vanvitelli" (University of Campania, Italy)
[5]QinetiQ (United Kingdom)

Abstract

The Group for Aeronautical Research and Technology in EURope (GARTEUR) is a multinational organisation to foster collaborative research within the field of aeronautics and build technological competitiveness for the European Aerospace Industry. Originally formed in 1973 by France, Germany and the United Kingdom it was later joined by the Netherlands, Sweden, Spain and Italy. The group has launched more than 140 research projects within its five different Groups of Responsables (GoR): Aerodynamics, Aviation Security, Flight Mechanics Systems and Integration, Rotorcraft, and Structures and Materials (SM). GARTEUR covers both civil and military technology, and it is a unique forum with a flexible approach open to aeronautical experts from academia, research establishments and industry.

As part of the GARTEUR SM GoR, the Exploratory Group EG-45 dedicated to the “Characterization and modelling of CMC submitted to severe thermo-mechanical loading” was established to coordinate activities relating to CMC structures. Currently, Office National d'Études et de Recherches Aérospatiales (ONERA), Netherlands Aerospace Centre (NLR), German Aerospace Center (DLR), University of Campania Luigi Vanvitelli, and QinetiQ plan to propose an Action Group dedicated to the characterization of the mechanical properties and modelling of SiC_f/SiC materials, submitted to high mechanical loadings and extreme thermal conditions.

Keywords: Ceramic Matrix Composite Materials (CMC), behaviour, damage, failure, GARTEUR

https://doi.org/10.71945/icas2026_1004

1. General Introduction

The standards recommended by the Advisory Council for Aeronautics Research in Europe (ACARE) in 2030 require the next generation of civil aircraft engines to reduce their fuel consumption and environmental footprint. Reducing the mass of structural components through the introduction of innovative composite materials, including in the hot parts of engines, is therefore a major industrial challenge. Ceramic materials have high melting points but are inherently brittle and lack toughness. It is precisely to overcome these major drawbacks that Ceramic Matrix Composites (CMC) are developed. Due to their excellent mechanical properties up to over 1500°C, they are therefore potential candidates for the manufacturing of some hot parts in future commercial aircraft engines [1]. It is therefore essential to be able to characterize CMC materials and assess their performance at ever-higher temperatures in order to ensure the durability and performance of hot components.

In order to prevent fibre breakage, which would lead to the failure of the material, two families of ceramic composite materials are commonly developed: weak interface or weak matrix composites (Figure 1). The first approach consists in the insertion of a mechanically weak interphase between the fibres and the matrix with the objective to divert the cracks and protect the fibres that ensure the mechanical strength of the material. The second approach, which is more recent and less conventional, introduces some voids into the matrix. The energy required for a crack to propagate through the matrix is less than that required for it to propagate through a fibre, resulting in the deviation of the crack at the interface fibre/matrix.

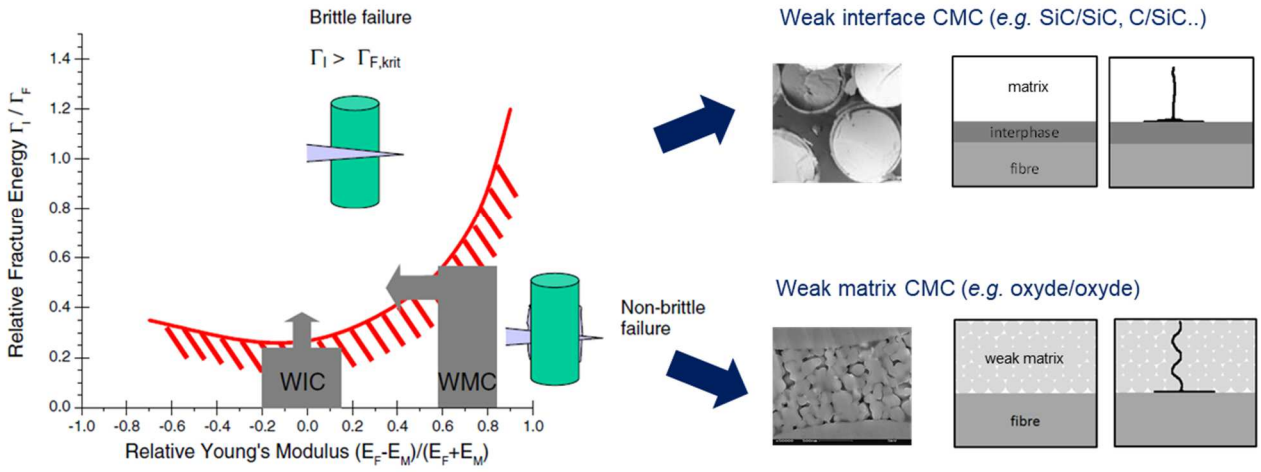


Figure 1 – Presentation of the two main families of ceramic composites materials

Among weak interface CMC, the main fibre/matrix combinations are as follows: C_f/C, C_f/SiC, SiC_f/SiC. As early as the 1960s, C_f/C CMC were developed, for example to provide thermal protection in various aerospace and military applications. The advantage of these materials consists in their resistance to high temperatures and to thermal shocks, their low density and non-brittle behaviour. However, their resistance to high temperature remains limited, due to their sensibility to oxidation at temperatures above 400°C. One of the solutions developed to overcome this limitation consists in replacing the matrix, and possibly the fibres as well with Silicon Carbide (SiC).

These materials (SiC_f/SiC) are therefore commonly used in the aerospace industry for their resistance to high temperatures and their good mechanical properties. The main drawback remains

their manufacturing costs and it is essential to optimise testing and to develop reliable damage and failure models.

Performing multi-instrumented (digital images correlation, acoustic emission, infrared thermography, CT-scan) mechanical tests at high temperature remain very complex on CMC coupons, as illustrated in Figure 2, and current standards must be improved to determine precisely damage and failure scenario, which are strongly linked to the constituents and the architecture as demonstrated in [2, 3, 4]. Moreover, tests performed on structures at higher levels in the pyramid of certification are not standardised and should be considered to better prepare tests such as bending on L-angle specimens for instance.

Nevertheless, the efficient design of such composite parts cannot rely only on test campaigns, due to the cost of such materials, and therefore requires the use of damage and failure approaches, physically based but ensuring the requirements of a design office in aeronautics in terms of modelling complexity, robustness and computational costs [5,6,7].

There are very few studies focusing on thermo-mechanical testing and advanced damage simulation on CMC demonstrators, representative of industrial applications at high temperatures, due to the difficulties associated to manufacturing, testing and simulation of CMC structures.

The objective of the project is to understand the damage and failure mechanisms under static and fatigue loading at very high temperatures of a SiC_f/SiC material. It is also to propose and validate on a CMC demonstrator, damage and failure models under static and fatigue loading, by comparing tests with simulation results. Particular attention should be paid to fatigue loading, as these materials are susceptible to damage from the very first application of a static load with a gradual decrease of their mechanical properties until failure occurs.

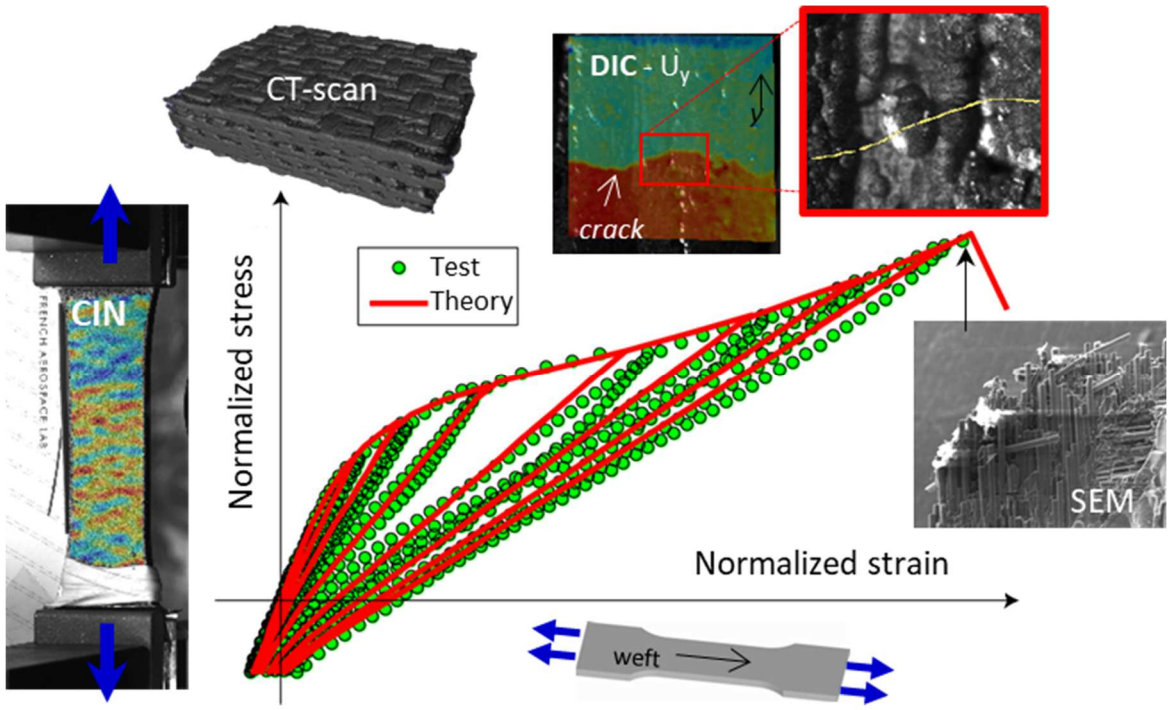


Figure 2 - Multi-instrumented tensile test on Sic/Sic 3D woven composite material [8]

2. Objectives of the project

To meet the general objectives of the project, several scientific and technological objectives need to be addressed (as illustrated in Figure 3):

- Define standard tests to measure mechanical properties (behaviour, damage, failure) at high temperatures: Multi-instrumented tests will be performed at different temperatures to characterize thermo-mechanical properties of the studied SiC_f/SiC material. The current standards for CMC materials will be updated/improved at the coupon level and could be proposed for L-angle specimens. Recommendations for advanced instrumentation of such complex tests with digital images correlation, infrared cameras, acoustic emission, or optical analysis (SEM) will be drawn.
- Propose damage and failure models at different scales to predict behaviour, damage, failure and fatigue lifetime: Multiscale damage models, considering the meso-constituents at elementary entities for modelling, will be developed associated to advanced regularization methods, such as Phase-Field, in order to improve the comprehension of the damage mechanisms and the failure process. This multiscale model could be also used in order to feed a macroscopic damage model based on continuum damage model, which can be applied on large composite structures. A special attention will be paid to modelling of delamination in multi-layered 2D woven composite parts.
- Manufacturing, testing and simulation on a CMC demonstrator to validate the developments proposed by the consortium: In order to validate the developments performed by the consortium considering both manufacturing, testing and simulation aspects, a demonstrator representative of industrials application will be proposed. Multi-instrumented thermo-mechanical tests on this demonstrator will be carried out considering real thermo-mechanical loading (with temperature gradient), as it can be performed at ONERA and/or DLR. Then, digital twins of the demonstrator will be generated and simulated in order to compare predictions with available test results. A special attention will be paid to computational strategies and methodologies in order to compare tests and simulations in a quantitative way.

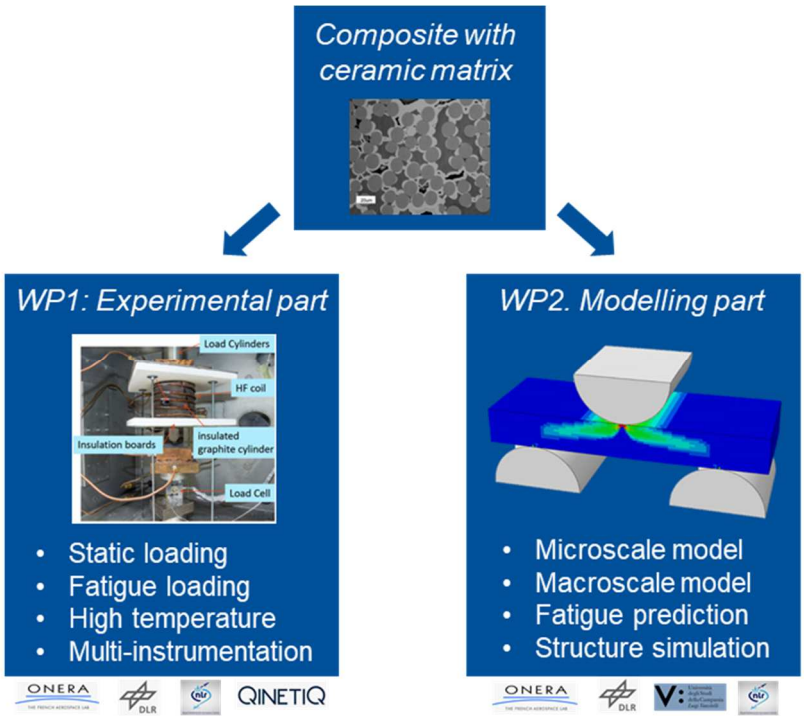


Figure 3 - Global overview of the project

3. Experience and activities of partners

The experience and the activities planned by each partner are briefly described below:

- ONERA has been working on CMCs for over 30 years, with the aim of developing models that can be used by design offices for structural analysis. ONERA will lead the project and will be involved in both multi-instrumented tests – necessary to fully understand the degradation mechanisms, which require detailed observations – and in the development of microscale and macroscale models to reproduce the observed physical mechanisms.

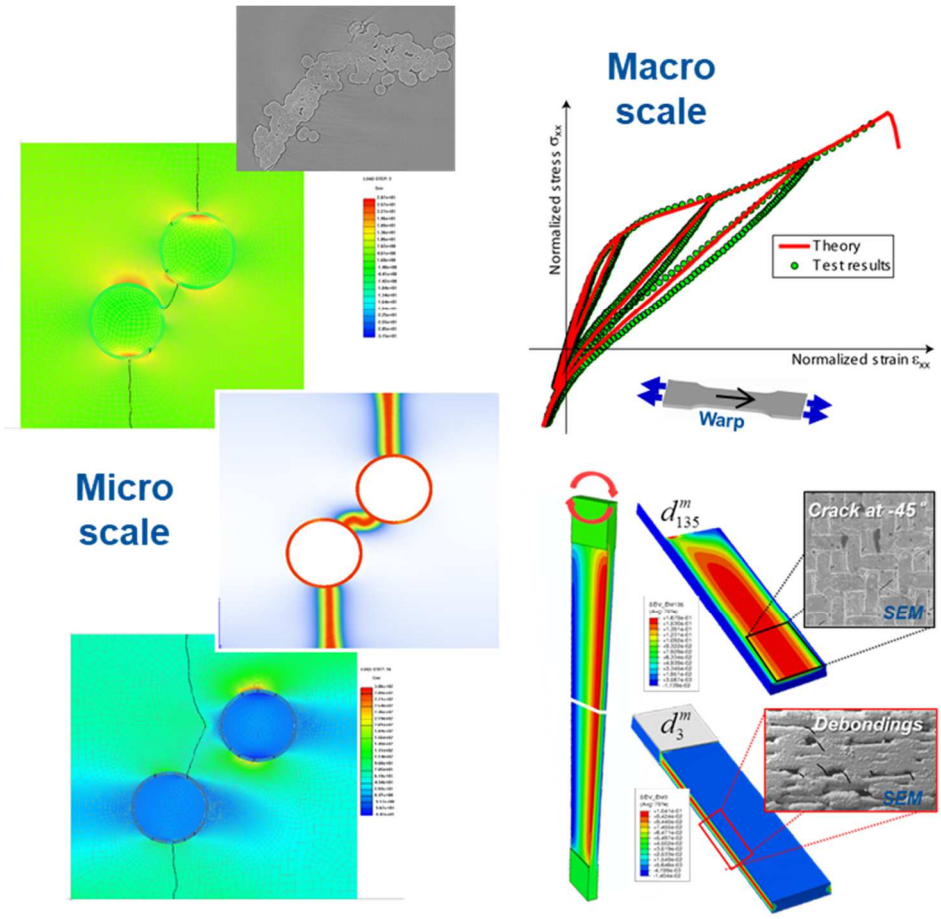


Figure 4 - Study of degradation mechanisms through microscale and macroscale tests and models developed at ONERA

- NLR will be involved in the experimental part to measure mechanical properties of the material.

- DLR will concentrate on the integration of numerical and experimental methodologies to advance the study of CMCs. Through multiscale simulations, the research will bridge microscopic damage evolution with macroscopic material behaviour. By explicitly incorporating microscopic crack propagation, this multiscale framework will systematically capture the diverse failure mechanisms of CMCs. These computational models will be validated using specialized test rigs and in-situ measurement techniques. Furthermore, experimental campaigns under severe thermo-mechanical loading conditions will incorporate multiaxial testing to comprehensively characterize CMC performance.

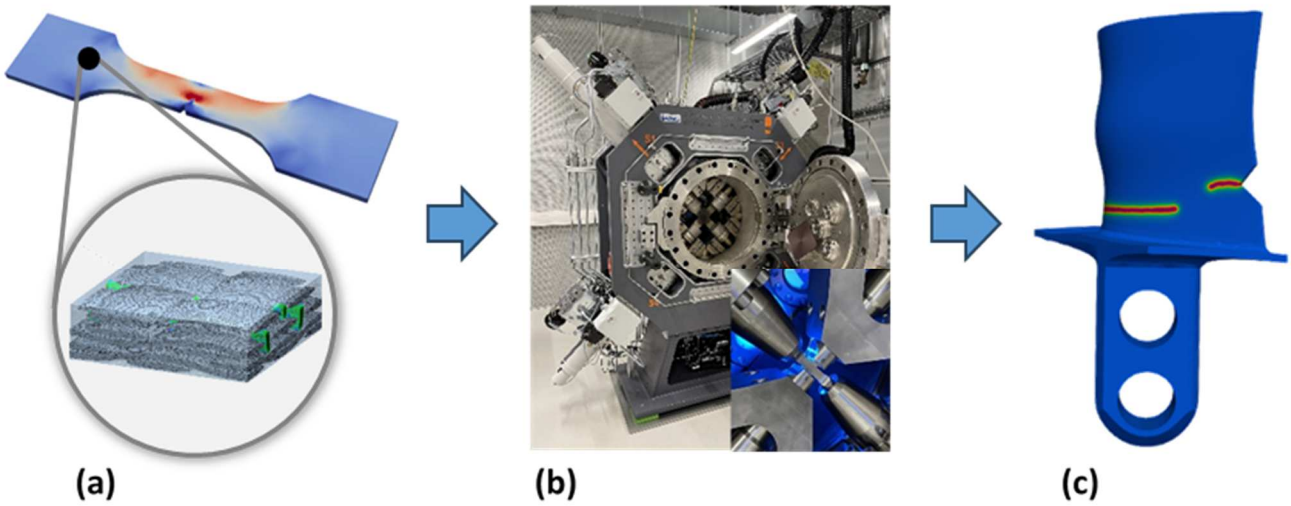


Figure 5 - Coupling of numerical and experimental methods, including (a) multiscale simulations and (b) validation procedures with unique test rigs for (c) failure predictions of turbine engine components. The design of the blade was generated by the Turbine Department of the DLR-Institute of Propulsion Technology

- The University of Campania Luigi Vanvitelli will play a key role in the numerical modelling activities within the project, with a specific focus on the development of advanced finite element (FE) models for the simulation of the structural behaviour of Ceramic Matrix Composites (CMCs) under operational thermo-mechanical loading conditions. The contribution of the University of Campania will primarily focus on the formulation and implementation of FEM-based approaches capable of accurately capturing the progressive damage evolution in SiC/SiC composites subjected to combined mechanical loads and high-temperature environments. Attention will be devoted to the identification and modelling of the damage mechanisms governing the material response, including matrix cracking, fibre/matrix debonding, fibre failure, and delamination in multi-layered architectures. The modelling activity will be structured according to a multi-scale approach. In an initial phase, the focus will be on the coupon level, where detailed finite element models will be developed to simulate standardized tests on small-scale specimens. These simulations will enable a comprehensive investigation of the onset and evolution of damage mechanisms under controlled loading conditions, as well as their interaction with thermal effects. Experimental data obtained from testing campaigns will be exploited for model calibration and validation, ensuring the predictive capability and robustness of the proposed approaches. In a subsequent phase, the modelling framework will be extended to the subcomponent level, where more complex geometries and realistic boundary conditions will be considered. This step is essential to link the material characterisation to structural application, allowing for the assessment of the structural integrity of representative components under service-relevant thermo-mechanical loading scenarios. Overall, the activities carried out by the University of Campania will contribute to the development of reliable and predictive modelling tools for CMCs, enabling a consistent comparison between experimental observations and numerical

simulations, and ultimately supporting the design of high-temperature composite structures for advanced aeronautical applications.

- QinetiQ will manufacture coupons using processes they have developed over the past 7 years. The systems will be developed to the requirements of the consortium and will be provided free of charge. Chemistry, fibre reinforcement type and geometry will be arranged to give the greatest benefit to the characterisation and associated modelling campaign. This may include samples made from SiC/SiC, SiC/Cf, and other fibre types as well as SiCN/SiC where relevant. Test samples may be manufactured with multiple dimension curvatures as well as multi-ply or 3D weave architectures and will be selected based on initial discussions and experimental planning with the consortium.



Figure 6 - Examples of QinetiQ samples, with different sizes and shape complexity

4. Conclusion

This paper outlines the work carried out within the EG-45 Exploratory Group on Ceramic Matrix Composites, as well as the work planned within the framework of the upcoming Action Group of GARTEUR SM (Structures and Materials). The partners participating in SM-EG45 are ONERA, NLR, DLR, university of Campania and QinetiQ.

The number of CMC coupons tested remains limited compared to metallic or organic matrix composite materials due to the cost of these materials. Furthermore, multi-instrumented tests at different temperatures, which enable the generation of quantitative data comparable to simulation results, are costly and require a significant expertise, both in the development of the tests and in their analysis. Therefore, the development of multi-instrumented tests protocols for CMCs is one of the main project's objectives. Another focus is the development of damage and failure models, as well as the comparison of structural simulation predictions with the results of multi-instrumented tests at high temperature.

References

[1] Naslain R., Design, preparation and properties of non-oxide CMCs for application in engines and nuclear reactors: an overview, Composites Science and Technology 64 (2) (2004), 155-170.

[2] Aubard X., Modélisation et identification du comportement mécanique des matériaux composites 2d SiC/SiC, Thesis/dissertation, Doctorate thesis of Université de Paris VI (1992).

[3] Gasser A., Ladeveze P., Poss M., Damage mechanisms of a woven SiC/SiC composite: Modelling and identification, Composites Science and Technology 56 (7) (1996) 779-784.

[4] Lamon J., A micromechanics-based approach to the mechanical behavior of brittle-matrix composites, Composites Science and Technology 61 (15) (2001) 2259-2272.

[5] Ladeveze P., Gasser A., Allix O., Damage mechanisms modeling for ceramic composites, Journal of Engineering Materials and Technology 116 (3) (1994) 331-336.

[6] Maire J.-F., Chaboche J.-L., A new formulation of continuum damage mechanics (cdm) for composite materials, Aerospace Science and Technology 1 (4) (1997) 247-257.

[7] Marcin L., Maire J.-F., Carrrer N., Martin E., Development of a macroscopic damage model for woven ceramic matrix composites, International Journal of Damage Mechanics 20 (6) (2011) 939-957.

5 Contact Author Email Address

Florence.roudolff@onera.fr

6 Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third-party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.