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PROPOSITION DE SUJET DE THESE

Intitulé : Experimental and numerical study of the damage behaviour of a carbon/carbon composite material subjected to thermo-mechanical loading

Référence : **MAS-DMAS-2025-40**
(à rappeler dans toute correspondance)

Début de la thèse : 01/10/2025	**Date limite de candidature :** 02/12/2025

Mots clés

Ceramic matrix Composite, Thermo-mechanical test, Damage modelling, FE simulation

Profil et compétences recherchées

Master's degree in research or from a prestigious university.
Good knowledge in non-linear finite element simulations.
Good knowledge of damage mechanics.
Interest in conducting instrumented and temperature tests.
Very good level in English and French (speaking / writing)

Présentation du projet doctoral, contexte et objectif

Ceramic matrix composites (CMCs) are considered for industrial applications [1] when the part is subjected to high mechanical stress combined with high temperature. Various applications can be enumerated: fan blades or plugs for aeronautics, thermal protection for space or nuclear applications, brakes for the automotive and aeronautical industries, and also various parts for military applications. Among the different types of ceramic matrix composites, carbon/carbon (C/C) composites are excellent candidates for military and civil applications. Their high mechanical stiffness and strength, even at high temperatures, make them preferred over metallic solutions, considering the trade-off between mass, performance and cost. However, for the use of a new C/C composite design, an in-depth understanding of the damage scenarios of the specific C/C material at ambient temperature, and also at temperatures of interest remain a necessity. Due to the manufacturing costs associated with such advanced materials, the design of composite parts cannot be based solely on testing. The analysis should also include finite element simulations accounting for the material specific mechanical behaviour and its failure modes. To demonstrate the predictive capabilities of such a model, a comparison must be conducted with advanced multi-instrumented tests, where real complex thermo-mechanical loads that includes severe thermal gradients are used.

The objective of the present thesis is to develop a methodology to predict the damage evolution within the C/C composite material provided by DSO subjected to different loadings applied at different temperatures. This thesis is divided into three main parts: (i) the study of damage mechanisms in the C/C material at ambient temperature and (ii) at three higher temperatures, a companion damage model will be developed to simulate the C/C thermo-mechanical behaviour, constructed with experimental observations. Finally, (iii) a validation phase of the proposed model will involve an assessment of the FE simulations with respect to advanced multi-instrumented thermo-mechanical tests carried out in a controlled environment.

The *first part* will consider multi-instrumented tensile tests at ambient temperature to determine the damage scenario up to failure. These tests will be instrumented with acoustic emission (to detect damage onset), digital images correlation (to measure displacement and strain fields during the test but also to observe cracks) and extensometer (to measure macroscopic strain). SEM analysis and CT-scan can be performed post-mortem to analyse the failure pattern. Tensile tests will be performed at 0° and 45° to determine the orientation of cracks within the material [2]. Based on the existing ONERA Damage Model (ODM) [3], a new thermo-dynamical damage model will be proposed for the C/C material studied. This model will first be developed and tested for a unique Gauss point using Matlab at the material level. Then the model will be implemented in the commercial FE code Abaqus/Standard.

The *second part* consists of carrying out instrumented tensile tests at different uniform temperatures. The procedure uses an oven where the environmental conditions are controlled to avoid the material oxidation. Three temperatures, 400°C, 600°C and 900°C, will be considered and once again, the two directions will be considered. Two specimens for each condition will be tested. These tests will be carried out at MATEIS laboratory, where an oven able to perform the vacuum around the specimen up to 1000°C is available.

Subsequently, the previously developed model will be extended to consider the influence of temperature. A high temperature is expected to affect the elastic behaviour, the damage onset and its propagation [4]. Again, the updated model will be tested at material level and integrated into Abaqus/Standard.

In the third part, to validate the proposed modelling framework, additional tests will be carried out at ONERA with the new SIMBA experimental device. This experimental device allows the application of a tensile mechanical load while the specimen is heated by a laser. The induced thermal gradient is more representative of the real conditions found in industrial application. In addition, the test is carried out in a controlled environment, avoiding oxidation phenomena. This test will be highly instrumented, in order to record the boundary conditions that will feed simulations to validate the model. Due to the heterogeneous thermo-mechanical loading, a complex damage pattern is expected, differing from those observed in tests performed at uniform temperature, the proposed model will then be challenged.

The development of a robust numerical framework, constructed and validated with respect to multiple tests of growing complexity forms therefore the ultimate objective of the PhD work.

This work will be carried out mainly at ONERA in the Materials and Structures Department (DMAS), including testing and modelling parts. A partnership with the French laboratory MATEIS is planned, notably for the mechanical tests at high homogeneous temperatures. Finally, DSO located in Singapore, will supply the C/C samples. All partners will be involved in the supervision of the PhD thesis.

[1] R. Naslain, « Design, preparation and properties of non-oxide CMCs for application in engines and nuclear reactors: an overview », Compos. Sci. Technol., vol. 64, no 2, p. 155-170, févr. 2004.

[2] O. Siron et J. Lamon, « Damage and failure mechanisms of a3-directional carbon/carbon composite under uniaxial tensile and shear loads », Acta Mater., vol. 46, no 18, p. 6631-6643, nov. 1998.

[3] L. Marcin, J.-F. Maire, N. Carrère, et E. Martin, « Development of a Macroscopic Damage Model for Woven Ceramic Matrix Composites », Int. J. Damage Mech., vol. 20, août 2011.

[4] A. Débarre, C. Przybyla, F. Laurin, T. Jackson, et J.-F. Maire, « Characterisation and damage modelling of oxide/oxide composites considering temperature dependence », J. Eur. Ceram. Soc., 2024.

Collaborations envisagées

DSO in Singapore/ Singapore

MATEIS in Lyon/France

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