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A meso-scale model of progressive damage and failure in LSI-produced ceramic matrix composites for aerospace applications

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Abstract. The paper is focused on the development of a modelling approach for Ceramic Matrix Composites (CMC) laminates, produced through a cost-affordable Liquid Silicon Infiltration (LSI) technique. The objective is the development of a tool capable of evaluating the design values for the material in the presence of technological defects and complex geometrical features, which could be used at the level of structural elements of details of reusable space vehicles. The model exploits a bi-phasic decomposition to capture four important aspect of the material: the non-linear behaviour occurring when load is not applied in the fibre direction, the significant bending to tensile strength ratio, the role of matrix fractures in the failure process and the role of delamination phenomena in the response. The correlation with tensile and bending tests performed with different lay-ups indicates that the developed approach can fulfil such objectives and may be used in the definition of structural details and of damage tolerance of innovative space vehicles.

Introduction

Ceramic Matrix Composites represent one of the most promising solutions for the development of structures capable of performing structural roles at temperatures beyond 1000 °C, such as the ones occurring in re-entry or single-stage-to-orbit vehicles in space missions, or in hypersonic vehicles and in propulsive systems in the aerospace field [1].

The increasing demand for truly reusable space and hypersonic transport systems introduces significant issues regarding the structural integrity and the damage tolerance of such hot structures. The material cost is another critical aspect for the development of the next generation of space vehicles. The LSI technique, can significantly reduce the cost of the CMC production, with respect to more traditional techniques, like chemical vapour infiltration or polymer infiltration and pyrolysis [2], but the porosity levels and the possible occurrence of technological defects can increase, thus emphasizing the need for controlling damage development in the material [4].

The activity presented in this paper was performed within the project AM^3aC^2A, funded by the Italian Space Agency (ASI), aimed at developing develop multi-scale approaches for the structural integrity of CMC in reusable aerospace components. The objective was the formulation of a non-linear numerical approach to be used in models of CMC laminates at the level of structural details or element, with a ply-wise (meso-scale) approach. The prediction of the structural response in the presence of geometrical features such as holes, cutouts, highly curved parts, and macro-porosity is one of the final goal of model, which in this paper is proved capable to idealize the most important failure mechanisms and to capture the quantitative response of multi-directional CMC laminates in tension and bending, thus providing a proof of its potential.

Experimental characterization

A test campaign was conducted with the aim of obtaining the basic properties of the orthotropic C/SiC fabric plies produced through the LSI technique and, at the same time, of providing validation experiments for the model to be developed. Figure 1-A reports the stress vs. strain responses recorded in four types of quasi-static tensile tests on laminates with lamination sequence of $[0]_{20}$ ("*T0*"), $[45/-45]_{10s}$ ("*T45*"), $[30/-30]_{10s}$ ("*T30*"), and $[0/45/90/-45]_{5s}$ (*"TQI"*).

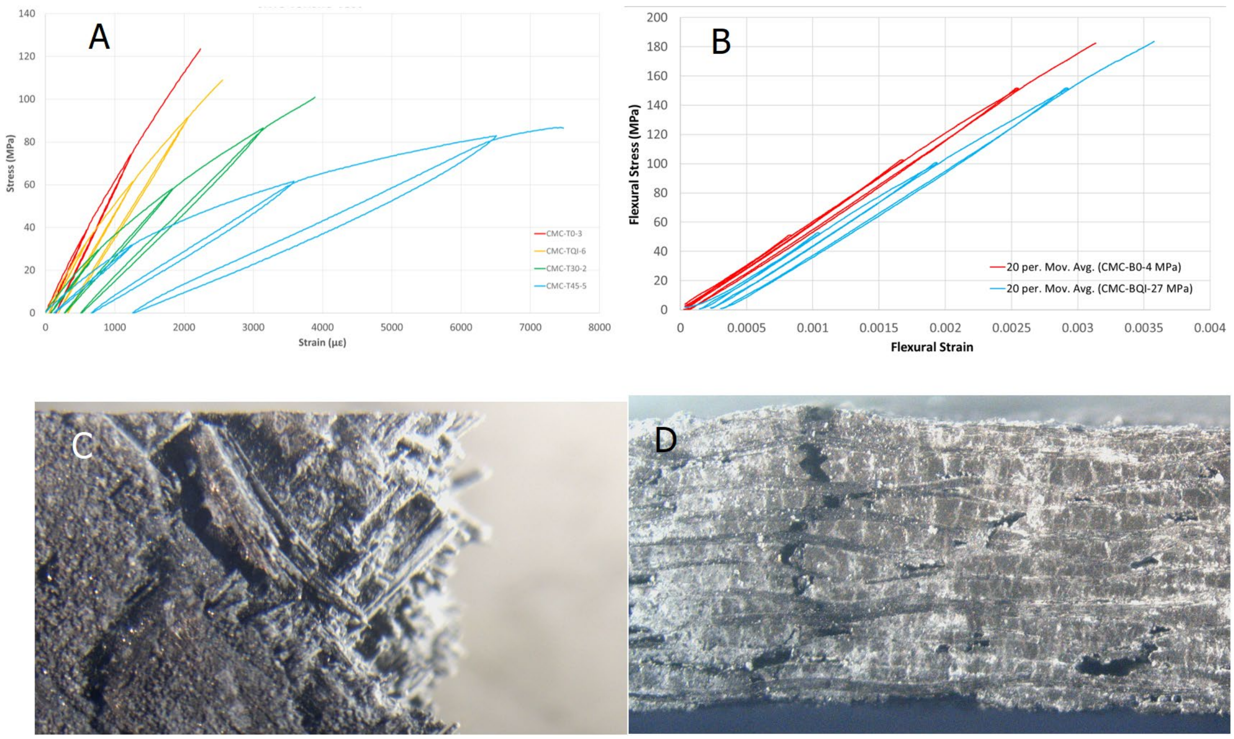

Fig. 1 – Response of tensile (A) and bending (B) test on CMC laminates, failure modes in "T45"(C) and "B0" tests (D)

The standard ASTM C1275-15 was taken as a guideline to design the specimens and perform the tests. All the specimens were dog-bone shaped, with (a total length of $200\ mm$, a gauge length of $45\ mm$, and an average thickness of 4.2 mm. All the tensile specimens were equipped with glass-fiber reinforced epoxy tabs to mitigate the risk of failures out of the grip. The stress vs. strain response reported in Fig. 1-B were obtained in two three-point bending tests performed on $[0]_{20}$ laminates (*"B0"*) and $[0/45/90/-45]_{5s}$ laminates ("BQI").

The response in the tensile tests was characterized by increasing non-linear behavior and ultimate strain at failure, as the percentage of fibers not aligned with the load application direction is increased. The maximum stress carried by the external plies of the laminate *B0* was significantly higher than the value recorded in the tensile "*T0"* stress. The failure mode in "*T45*" specimens indicated a diffused damage state in the matrix, as shown in Fig. 1-C, while the failure in "*B0*" test was characterized by a neat fracture in the 90°-oriented fiber yarns, while the 0°-oriented fibers do not show a clear fracture line (Fig. 1-D).

Overview of the numerical approach

The numerical approach adopted moved from the technique developed in [3,4] for polymer matrix composites. The CMC homogenized material model was decomposed into two idealized phases: fiber and matrix. The fiber were modelled through a layer of membrane element, which carried stress only in the fabric reinforcement directions, while the matrix was represented by solid elements. In general, the technique makes possible the representation of delamination without the use of zero-thickness cohesive elements, the development of different constitutive laws for matrix- and fiber-dominated responses, the representation of the interactions between matrix damage inside the plies and the delamination phenomena. The in-plane damage in the matrix was modelled by using a single scalar damage variable, as represented in Eq. 1. Such variable evolved with the distance from a threshold damage function, shaped as a Tsai-Wu criterion, expressed in Eq. 2. For the sake of brevity, the aspects related to the integration of delamination damage in the modelling technique are not reported (see [3,4] for further details).

$$\begin{bmatrix}\varepsilon_{11}^m\\ \varepsilon_{22}^m\\ \gamma_{12}^m\end{bmatrix} = \begin{pmatrix} \frac{1}{(1-d_m)E_{11}^m} & \frac{\nu_{21}^m}{E_{22}^m} & 0 \\ \frac{\nu_{12}^m}{E_{11}^m} & \frac{1}{(1-d_m)E_{22}^m} & 0 \\ 0 & 0 & \frac{1}{(1-d_m)G_{12}^m} \end{pmatrix} \begin{bmatrix}\sigma_{11}^m\\ \sigma_{22}^m\\ \tau_{12}^m\end{bmatrix} \tag{1}$$

$$f(\tilde{\sigma}^m) = \sqrt{F_1\tilde{\sigma}_{11}^m + F_2\tilde{\sigma}_{22}^m + F_{11}(\tilde{\sigma}_{11}^m)^2 + F_{22}(\tilde{\sigma}_{22}^m)^2 + 2F_{12}\tilde{\sigma}_{11}^m\tilde{\sigma}_{22}^m + F_{66}(\tilde{\tau}_{12}^m)^2} \tag{2}$$

Results and Conclusions

A couple of iso-damage surfaces are shown in black and red colors in Fig. 3-A. Figures 3-B and C present the finite element models of the tensile and bending tests, respectively. The need of modelling the influence of matrix damage on the failure led to calibrate a new surface for the peak stress carried by the matrix phase (in green in Fig. 3-B), beyond which an exponentially decaying strain softening regime was modelled. Such second surface and the limit stress carried by the fiber phase were not fixed in the models, but were statistically distributed in the elements of the models. The parameters of such distribution have been identified through a Monte-Carlo approach, considering the correlation with the ultimate strength in all the tests as main performance index.

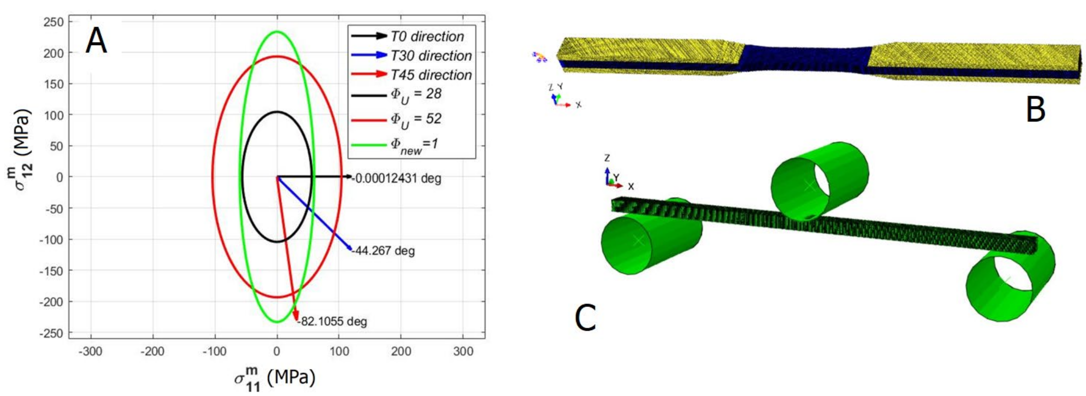

Fig. 3 – Tsai-Wu shaped surface for matrix damage evolution (A) and FE models of tensile (B) and bending (C) tests

The bi-phasic nature of the approach, the choice and the calibration of the damage evolution laws, the statistical distribution of the ultimate strength of the idealized phases led to obtain the results presented in Fig. 4, which indicate the all the quantitative and qualitative aspects of the responses are captured. In particular both the ultimate tensile strength in the "*T0*" test (Fig. 4-A) and the force vs. displacement response in the bending "*B0*" tests is obtained, thus indicating that the statistical distribution of properties can represent the bending/tensile strength ratio (Fig 4_D). Moreover, the localization of fracture can be represented, as shown in Fig. 4-E. For such localization, the integration of delamination damage in the analyses was found to play a fundamental role. Hence. the modelling approach was able of representing, without meshes at the sub-ply or microscopic levels, the fundamental quantitative and qualitative aspects of non-linear response and failure of the CMC material.

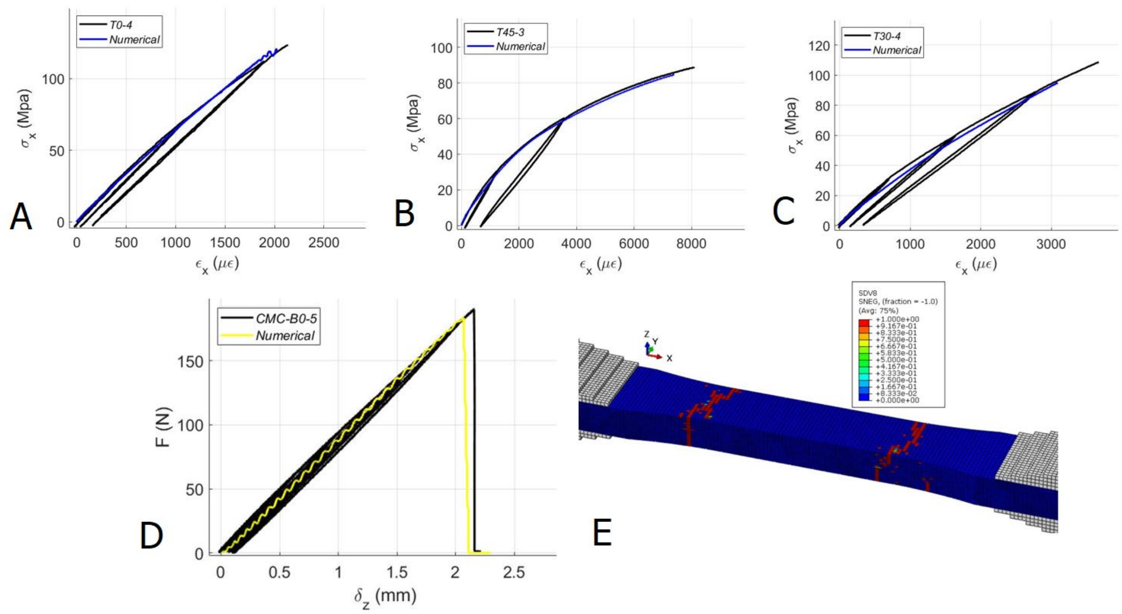

Fig. 4 – Numerical-experimental correlation in test “T0” (A), “T45” (B), “T30” (C), “B0” (D), and numerical failure mode (fiber damage) in “T30” analysis

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References

[1] H. Hald, Operational limits for reusable space transportation systems due to physical boundaries of C/SiC materials. Aerospace Science and Technology 7(2003) 551–9, https://doi.org/10.1016/S1270-9638(03)00054-3

[2] W. Krenkel, F. Berndt, C/C–SiC composites for space applications and advanced friction systems, Materials Science and Engineering: A 412 (2005) 177–81. https://doi.org/10.1016/j.msea.2005.08.204

[3] A. Airoldi, C. Mirani, L. Principito, A bi-phasic modelling approach for interlaminar and intralaminar damage in the matrix of composite laminates, Composite Structures, 234 (2020), 111747. https://doi.org/10.1016/j.compstruct.2019.111747

[4] A. Airoldi, E. Novembre, C. Mirani, G. Gianotti , R. Passoni, C. Cantoni, A model for damage and failure of carbon-carbon composites: development and identification through Gaussian process regression, Materials Today Communication, 35 (2023) 106059. https://doi.org/10.1016/j.mtcomm.2023.106059