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Design and Post-Test Analysis of PWT Testing on CMC and UHTCMC Materials

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Abstract

The thermal protection systems for reusable space transport vehicles primarily rely on ceramic matrix composite materials, known as CMC (Ceramic Matrix Composites). C/SiC (Carbon/Silicon Carbide) represents a solution for the development of thermostructures capable of operating at temperatures up to 1600°C. In Europe, they have been developed in many Space Vehicle projects (X-38, EXPERT, IXV). To date, their usage needs to be verified for reusability within a structural philosophy that involves assigning increasingly significant structural tasks to C/SiC structures under conditions characterized by exposure to significant thermal fluxes for extended periods. The AM3aC2A project aims to develop numerical tools for multi-scale modeling dedicated to space-specific materials and their integration with experimental protocols to define a design methodology for reusable space thermal structures, not only considering C/SiC but also considering UHTCMCs, a new class of materials primarily based on matrices of metallic borides reinforced with carbon fibers and aim to achieve operating temperatures exceeding 2000°C. Challenges include complex material behavior and the need for conservative designs due to limited knowledge. Within the AM3aC2A project, the Italian Aerospace Research Centre (CIRA) has been involved to perform PWT design and testing activities, while Politecnico di Milano was involved for post-test analyses on the CMC and UHTCMC samples. Italy's involvement in this project enhances its capabilities in critical technologies and opens opportunities for a wide range of applications, from space propulsion to aviation, energy, and automotive sectors. By reaching Technology Readiness Level 5 (TRL 5), Italy can demonstrate its national capacity for designing and testing ceramic matrix composite components, fostering innovation and international competitiveness. The project holds great promise for future space programs and technological advancements in various industries.

Keywords: *CMC, UHTCMC, C/SiC, Plasma Wind Tunnel testing*

Nomenclature

BC(s) – Boundary Condition(s)
C/SiC – Carbon/Silicon Carbide
CFD – Computational Fluid Dynamics
C_h – Convective Heat Flux coefficient
CIRA – Centro Italiano Ricerca Aerospaziale
CMC – Ceramic Matrix Composite
FEM – Finite Element Method
IXV – Intermediate eXperimental Vehicle
PWT – Plasma Wind Tunnel
q_w – Wall Heat Flux
T_0 – Stagnation Temperature
TA – Test Article
TRL – Technology Readiness Level
T_w – Wall Temperature
UHTCMC – Ultra High Temperature CMC
ε – Emissivity
σ – Stefan-Boltzmann constant

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1. Test Demonstrator Design

The design of the test demonstrator (for UHTCMC and Isicomp samples) was based on the results related to CFD and thermo-structural analyses that will be here presented.

1.1. CFD Analysis Overview

UHTCMC and CMC AM3aC2A TAs have been firstly assessed by means of a CFD analysis performed in the software Ansys Fluent. Before performing a CFD analysis directly on the TA, is firstly required to characterize the flow in terms of velocity temperature, pressure and species concentrations. In order to do that a first 2D axis-symmetric analysis is performed on Scirocco Probe, considering the initial conditions given by the facility (Current, mass flow rate -> Total Pressure, Total Enthalpy). These conditions are inserted as input at the inlet of the Nozzle and then the CFD analysis is performed. The data extracted from this analysis is Mach number, Pressure, Temperature and species concentration just before the bow shock. This data is then considered as input for an asymptotic 2D planar CFD analysis of AM3aC2A TA. The numerical procedure is schematically reported in **Fig 1.**

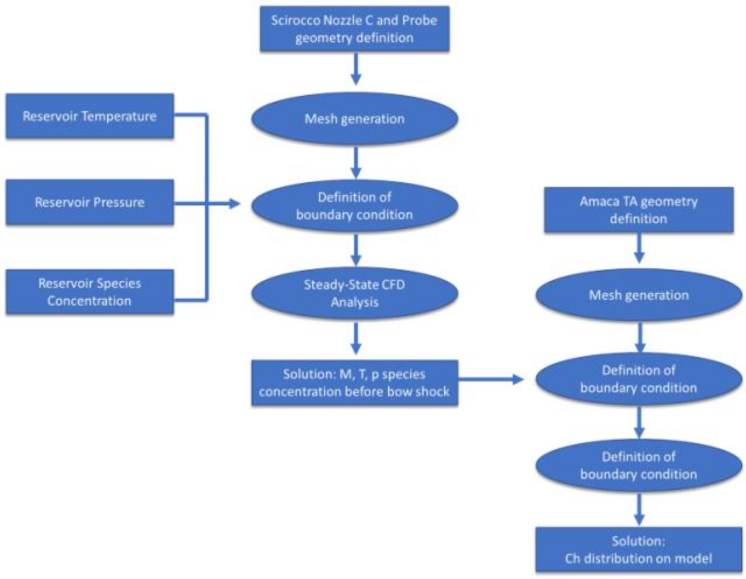


Fig 1. CFD numerical procedure

1.2. CFD Analysis numerical model and results

The CFD has been performed using ANSYS Fluent. The mesh is shown in **Fig 2,** while the BCs and the solver settings are shown in **Fig 3.**

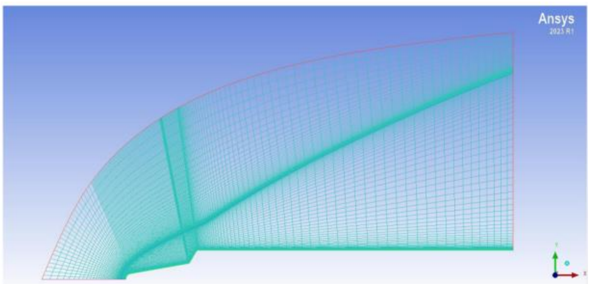


Fig 2. CFD Mesh

Solver	Density-Based, Steady, Planar
Models	Energy equation, Two-Temperature Model, Laminar flow
Species	Volumetric Reactions, 5-species Park model for air
Inlet – pressure far field	P = 54.96 Pa, M = 7.333, T = 678.88 K
Species Mass Fractions @ Inlet	N = 0.022, O2 = 5.88e-5, O = 0.23, NO = 8.82e-6
Wall	Radiative Equilibrium, Zero Diffusive Flux
Methods	Implicit formulation, AUSM Flux Type
Discretization	Second Order Up for Flow and Two-Temperature model

Fig 3. CFD settings and BCs

$$Ch = \frac{\dot{q}_W}{(T_0 - T_W)} \qquad (1)$$

$$\dot{q}_w = \sigma * \varepsilon * T^4 \qquad (2)$$

The main results of the CFD analysis are shown in the following pictures. **Fig 4** shows the distribution of Wall Temperature and Convective heat transfer coefficient (Ch) along the model. The Ch is evaluated as expressed in equation (1), while the wall heat flux $\dot{q_w}$ is calculated using equation (2).

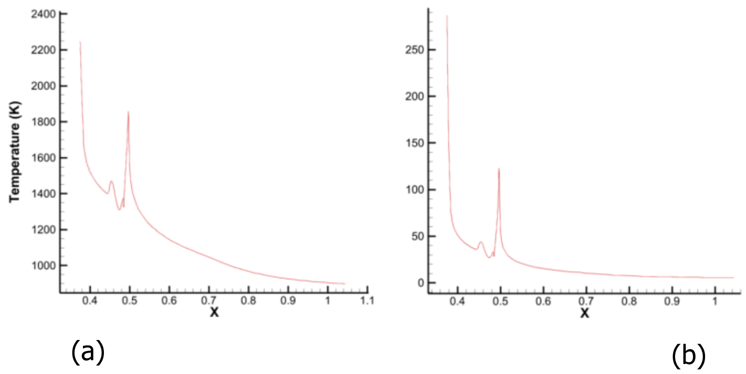


Fig 4. Wall Temperature (a) and Ch distribution (b) along the model

1.3. Thermo-structural Analysis Overview

CMC AM3aC2A Test Article behaviour has been assessed by means of the FE method implemented in the software Ansys Workbench. A transient thermal analysis along the trajectory is performed to evaluate the time dependent temperature of the structure. After that a steady-state thermo-structural analysis is performed at radiative equilibrium temperature to assess the capability of the structure to withstand the aero-thermal environment during the PWT testing conditions. The flow-charts of the two procedures are reported in **Fig 5.**

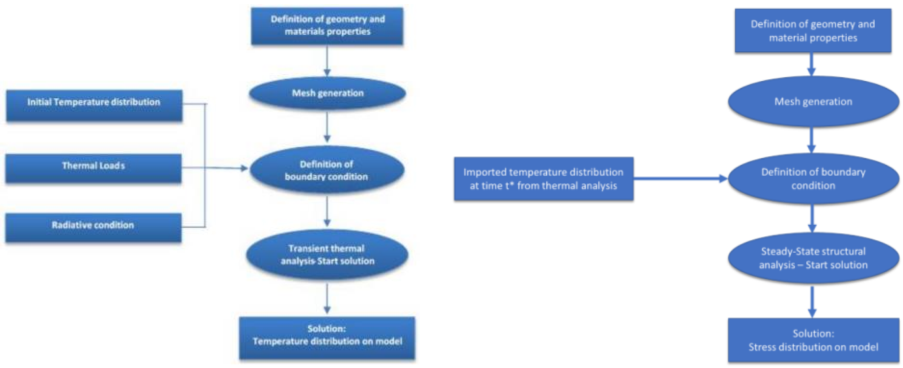


Fig 5. Thermo-structural numerical procedure flow charts

1.4. Thermo-structural analysis model and results

The FEM thermo-structural analysis has been performed using ANSYS Mechanical. The mesh used for both analyses is shown in **Fig 6**. Regarding the BCs, as shown in the flow charts, the thermal load in terms of **Ch** distribution is imported in the thermal analysis and then a radiation towards the surrounding environment has been applied. For the structural analysis, instead the output of the thermal analysis, in terms of temperature distribution (at steady-state condition), has been taken as input for the structural analysis performed considering both UHTCMC and Isicomp samples.

Fig 7 shows the results of thermal analysis in terms of temperature distribution on the TAs, considering a middle section for both UHTCMC and Isicomp. **Fig 8**, instead shows an overview of both stresses and deformation on the two different samples.

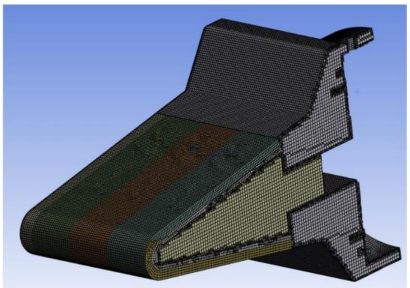


Fig 6. 3D Mesh used for FEM analyses

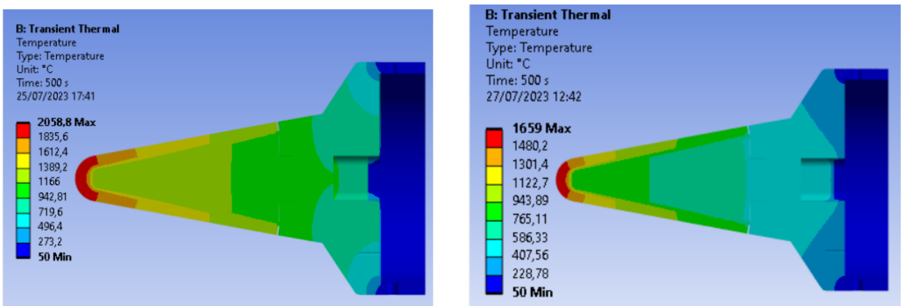


Fig 7. Temperature distribution on UHTCMC (left) and Isicomp (right) samples

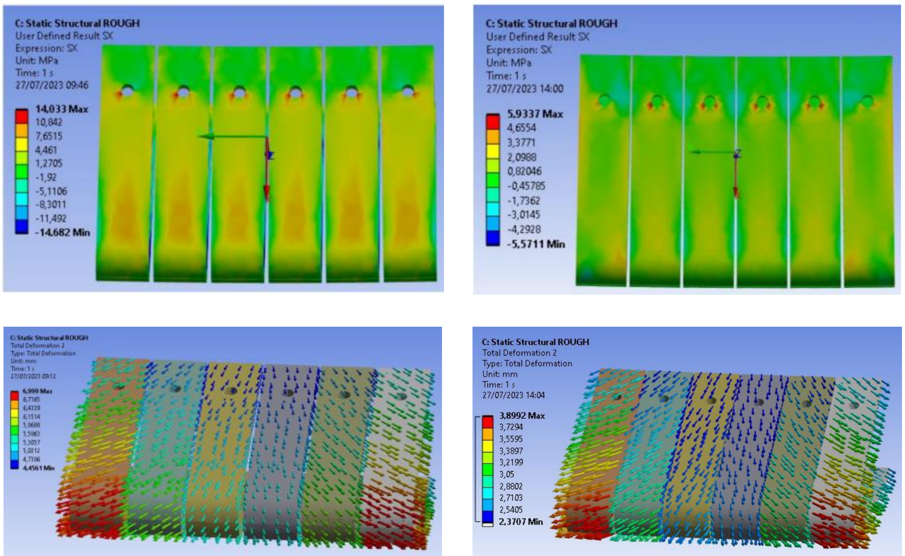


Fig 8. Maximum principal stresses and deformations on UHTCMC (left) and Isicomp (right) samples

2. Test Campaign

The test campaign was performed at CIRA Scirocco Plasma Wind Tunnel (PWT), which is the world's largest and more powerful hypersonic, high enthalpy, low pressure arc-jet facility in operation. Scirocco is powered by an arc heater of 70 MW maximum electrical power and it is able to generate a plasma jet of up to 2 meters of diameter, at Mach 12, for a test duration up to 30 minutes. The main goal of the facility is to qualify large scale test articles up to 600 mm in diameter, of Thermal Protection Systems (TPS), Hot Structures and Payloads of space re-entry vehicles. The test gas is a mixture of Air and Argon with a maximum mass flow rate of 3.5 kg/s.

Fig 9. CIRA PLASMA TESTING complex aerial view

Test campaign aimed at testing 6 UHTCMC samples and 12 ISiComp® samples installed on an ad hoc designed multi holder. Test condition were different for UHTCMC and ISiComp® samples.

In details:

- For UHTCMC test, Scirocco PWT was set to produce a high enthalpy flow such as to determine a surface temperature of 2000 °C.
- For ISiComp® test, Scirocco PWT was set to produce a high enthalpy flow such as to determine a surface temperature in the range 1600°C-1700°C.

In both cases, the test duration was of 300 seconds.

2.1. Test Articles

The samples tested were wedges with the size reported in **Fig 10**, installed on two ad hoc designed model holders. **Fig 11** shows two rendered view of the two model holders, the one on the left has been designed for the Isicomp samples while the one on the right was used for UHTCMC samples, which were shorter but with the same aperture angle.

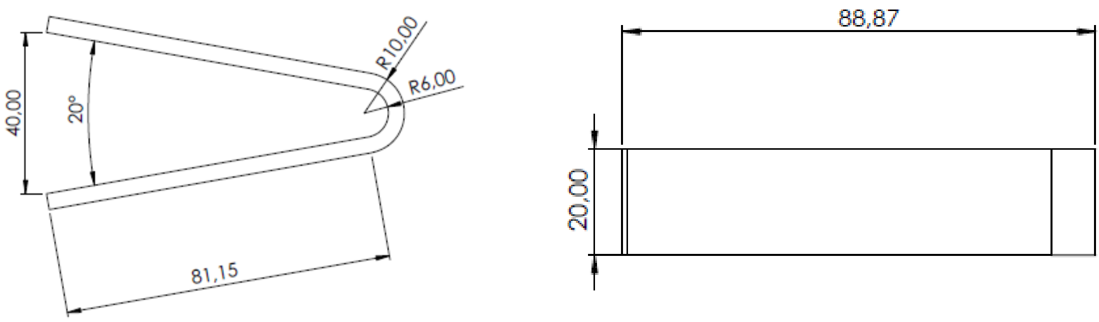


Fig 10. Isicomp sample shape geometry

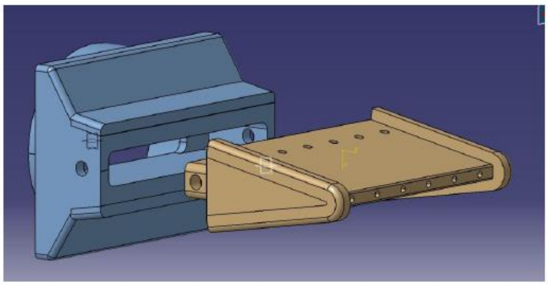
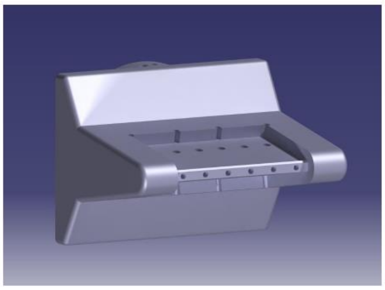



Fig 11. Sample holders rendered view

2.2. Instrumentation and data acquisition

To measure the temperature on sample backside, each holder -in details, four test articles: the two extremes and the two in the middle- was instrumented with thermocouple type B; moreover, the test articles were insulated from graphite by means of strip of Nextel, as shown in **Fig 12**.

In more details, for the test on UHTCMC materials, the backside temperature was measured for samples labeled with letters A, C, D, F; for the test on ISiComp materials, the backside temperature was measured for samples labeled with 3.1, 3.3, 4.1, 4.3, 6.1, 6.3, 8.1, 8.3.

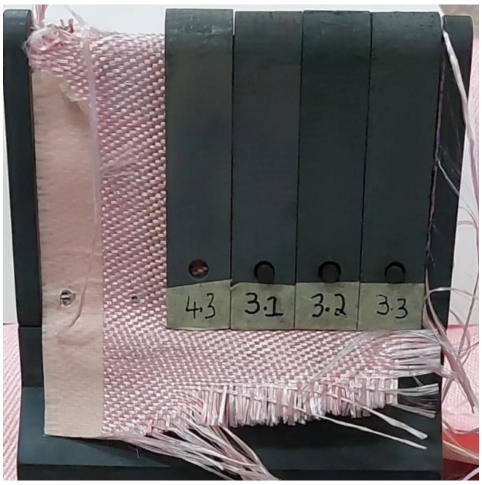


Fig 12. Nextel strip to insulate samples from graphite model holder

The facility Data Acquisition System also recorded other parameters, such as:

- Temperature on sample surface exposed to flow, measured using dual color pyrometers
- Temperature distribution on the exposed surface, evalued through IR thermocameras
- Temperature on sample surface not exposed to flow, measured using thermocouples

2.3. Test Results

The test campaign was not only successful, but also compliant with FEM thermal analyses performed pre-test and shown in **Fig 7**. As a matter of fact, thermographic images in **Fig 13** show how a maximum temperature of about 1670°C was reached at the stagnation point of the Isicomp samples and a maximum temperature of about 2100°C was reached at the stagnation point of the UHTCMC samples.

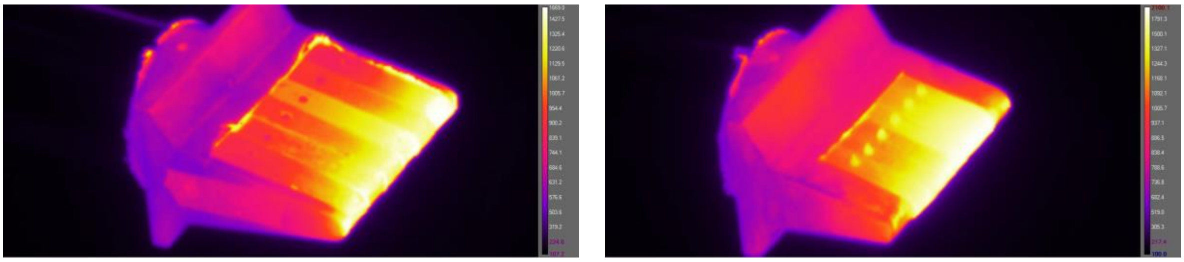
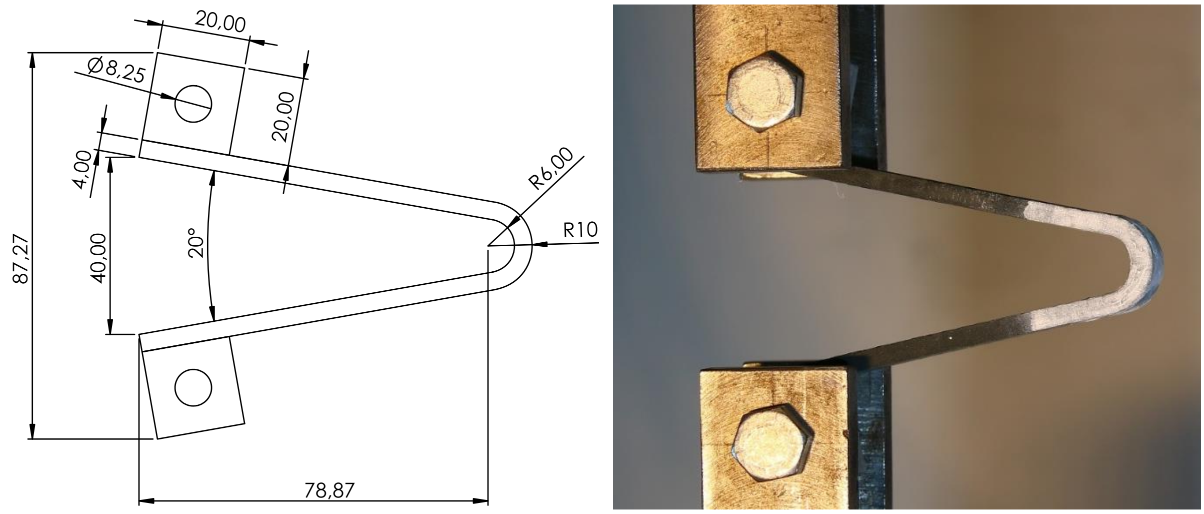


Fig 13. Temperature distribution on Isicomp (left) and UHTCMC (right) samples

3. Post-test Analysis

3.1. Mechanical tests setup

The mechanical tests were performed using an MTS 858 material testing system. To load the specimen two blocks were attached to each arm using Araldite 2012 structural adhesive. These blocks were drilled to be able to insert a pin in them and load the specimen using a hinge, thus avoiding the introduction of concentrated bending load. The specimen geometry with the blocks is reported in **Fig 14**a. The specimen was sprayed with white paint to identify the cracks that were opened during loading. An image of the specimen mounted in the testing machine is reported in **Fig 14**b.



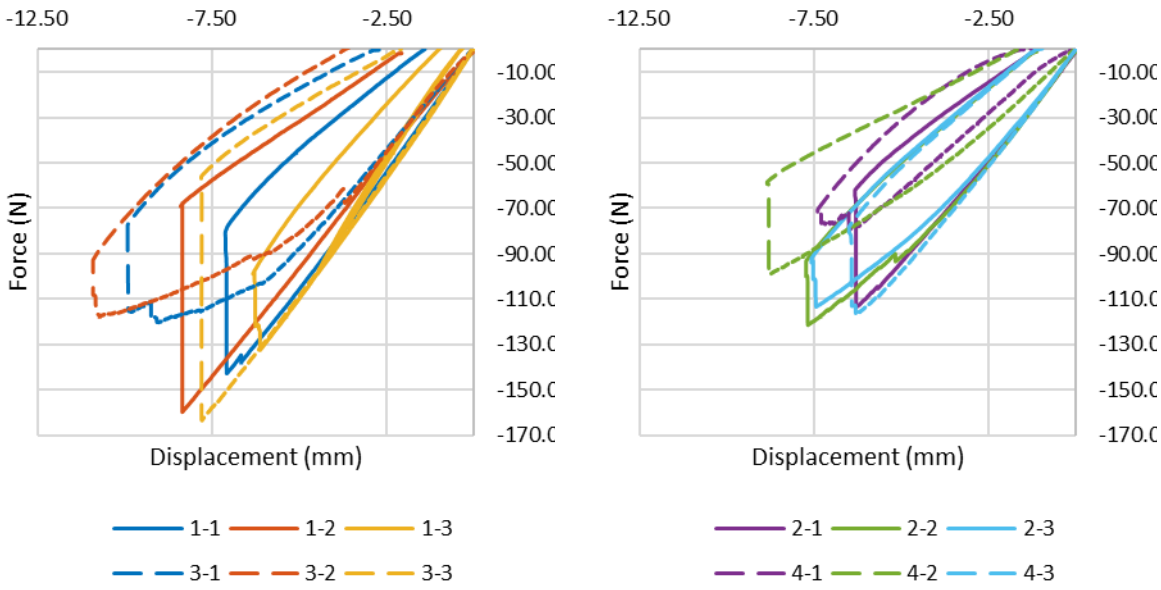
(a) **(b)**

Fig 14. (a) drawing of the specimen with loading blocks, (b) CMC specimen under testing

3.2. Mechanical tests on CMC specimens

$[0_6/45_{10}/0_6]$ closure

The effects of PWT testing were not identifiable by visual inspection, and the response of the specimens is reported in **Fig 15.** The failure mode was delamination in the arms for 3-1, 3-2, 4-1 and 4-2, which was not acceptable. This kind failure can be due to the worsening of a manufacturing defect during the high temperature cycle in PWT. Taking only the specimens showing acceptable failure mode, which was a crack on the "leading edge", the responses in plot *b* show a reduction of strength of about 25% with respect to plot *a*. This strength reduction comes from the introduction of butt joint, while looking at the response of 3-3 and 4-3 and comparing them with the non PWT exposed specimens (1-* and 2-*) the material shows no properties degradation.

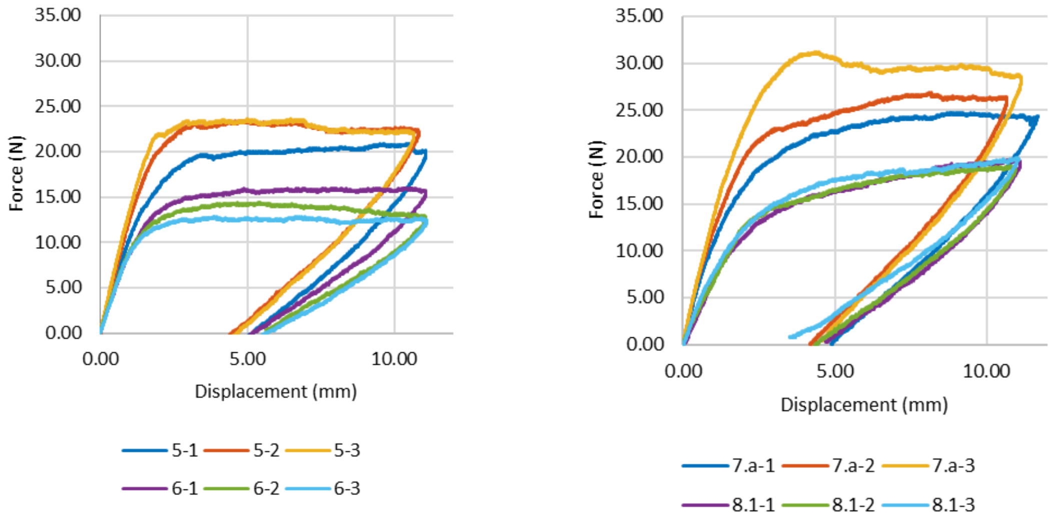


(a) **(b)**

Fig 15. Responses of the [0/45/0] specimens

[45_6/0_{10}/45_6] opening

The effect of PWT was clearly visible by visual inspection with destroyed coating and oxidized first layer. The response of specimen 5 and 6 is reported in **Fig 16.**a with a failure mode characterized by the opening of a crack network. This failure mode was replicated by specimens with delamination A, and the plot of **Fig 16.**b reports a similar behavior. Comparing **Fig 16.**a and b is clear that the material response seems to be unaffected by the presence of the artificial delamination. The response of the pre-cracked specimens shows a slightly higher strength with respect to undamaged specimens and a growing response after the non-linearity starts. The specimens degradation due to PWT is noticeable in both cases, with a reduction of strength of about 35%. This degradation affects both the elastic part of the response and the response as the crack network is developed.



(a) **(b)**

Fig 16. Response of [45/0/45] specimens without delamination (a) and with delamination type a (b)

3.3. Mechanical test on UHTCMC specimens

The tests on UHTCMC wedges were performed in the same way, even if using smaller specimens. The geometry adopted is shown in **Fig 17**. Six specimens were subjected to PWT testing, three produced by Spark Plasma Sintering (SPS), laminated in the plane containing the wedge profile and three produced by Polymer Infiltration and Pyrolysis (PIP), laminated following the curvature of the angle. A further SPS-produced specimen was obtained as a residual of the machining process and for this reason it has a smaller width. It was used as a reference since it wasn't PWT tested.

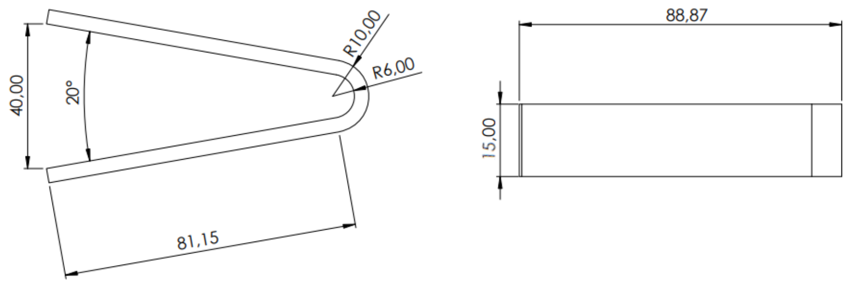


Fig 17. Drawings and measures of the wedge specimens adopted for PWT testing of UHTCMC.

Considering the novelty of a material such as UHTCMC, moreover subjected to PWT, and the reduced number of specimens, it was preferred to investigate different testing modes instead of focusing on the repeatability of the test. Nonetheless, UHTCMC always showed very repeatable behavior in all the experimental tests performed in the past. For this reason, some specimens were tested opening the wedge arms, some closing them. Loading/unloading cycles were performed on some specimens. Mechanical test campaign is still on-going.

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