# NUMERICAL APPROACHES TO DAMAGE TOLERANCE OF CARBOCERAMICS AND CARBON/CARBON MATERIALS

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CARBON CERAMIC BRAKES

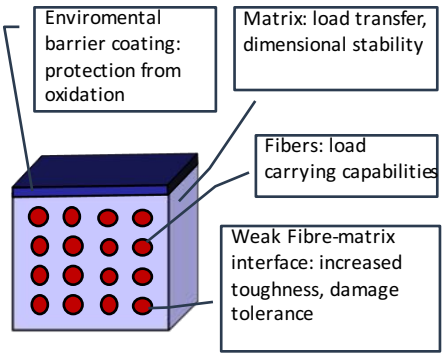
3 brembo Racing

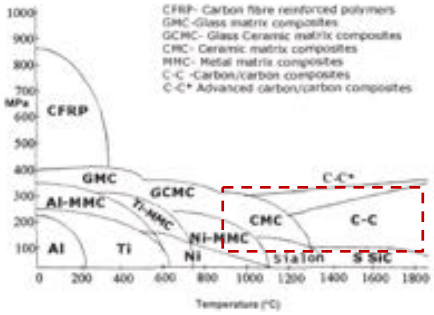
4 PETROCERAMICS
Turn natural complexity into technology

## CONTENTS

## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Ceramic Matrix Composites (CMC) and Carbon-Carbon (C-C) composite materials have been used in Thermal Protection Systems for space vehicles



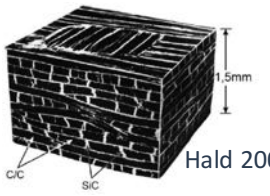

resistance to high temperature and appreciable mechanical properties



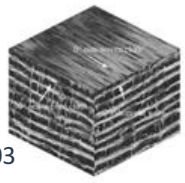
## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Ceramic Matrix Composites with C fibers and SiC matrix: potential to be used as structural material up to 1500° C

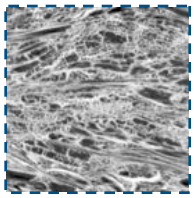
1-D, 2-D. 3-D and short fibers reinforcement architectures




Hald 2003



Mei & Cheng 2009



Airoldi et al. 2013

Processes: Polymer Impregnation and Pyrolisis (PIP), Chemical Vapour Infiltration (CVI), Liquid Silicon Infiltration (LSI)

Intensively studied for application in hot structures for NASA X-38, Hermes European Shuttle

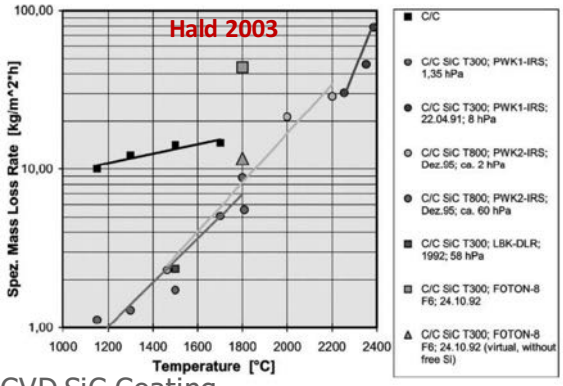
TRL such type of application 6-7 (Badini et. al, 2012)

## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Oxidation is one of the most critical issues for application

Porosity of SiC matrix prevents passivation
➡ oxidation

Progressive damage accumulation




- Possible solutions

Deposition of non-porous CVD SiC Coating

Multi-layer SiC laminates with different composition (Badini et al. 2012)
➡ Improved toughness

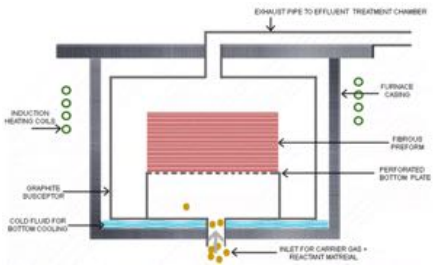


## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Carbon/Carbon material (studied since late 50's by USAF and NASA) can withstand to temperature higher than 2500 °C
- 1-D, 2-D, 3-D reinforcement architecture / Quasi 3-D with needling to improve interlaminar strength
- Low density (1.6 g/cc ÷ 2.0 g/cc), low CTE, high thermal conductivity
- Tensile strength up to 700 MPa
- Processes:

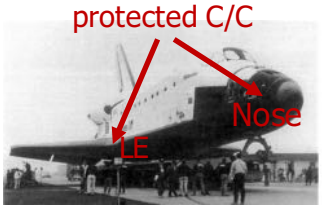
-Pyrolysis, Liquid infiltration, Chemical Vapour Infiltration

-Can take months for low-porosity densification

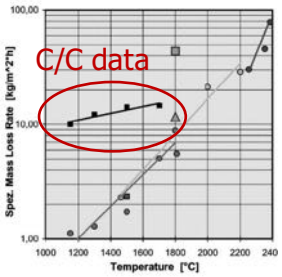


## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Space applications







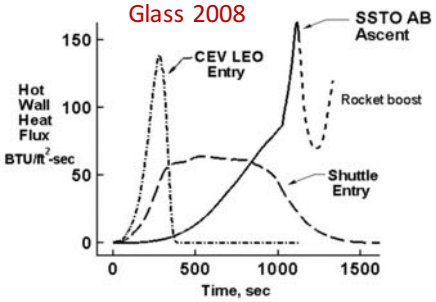

- Oxidation of carbon beyond 500 °C is the main drawback for structural applications where reusability is required
  - Protective layers must be used (SiC or $Si_3N_4$ layers)
  - Thermo-mechanical compatibility between C/C and protection is critical



## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Hypersonic air breathing vehicles involve severe thermal requirements (high peak and duration of heat flux)

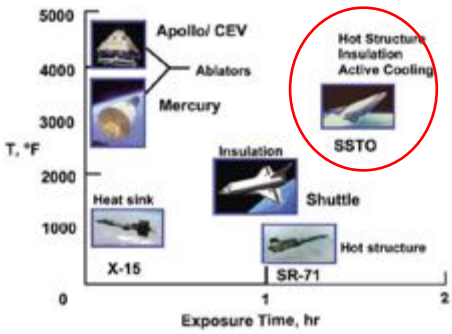
Glass 2008




CEV: Crew Exploration Vehicle (Orion)

SSTO AB: Single Stage to Orbit – Air Breathing during ascent

- Traditional concepts are inadequate

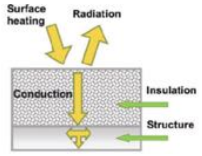



Glass 2008

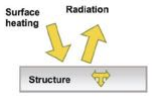
## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

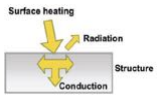
- Some traditional concepts

Insulated «cold» Structure (shuttle)

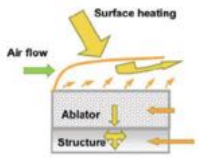



Heat sink/ Hot structure (X-15/SR-71)

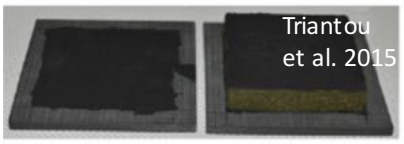



Ablative TPS (Orion)




- Concepts for hypersonic flight




Reusable C/SiC hot structure + ablative layer joined by graphite based adhesive

Semi-active and active cooling

Examples from Glass 2008



## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- Reusable CMC and C/C primary hot structures with additional protections could represent a fundamental enabling technology for hypersonic flight
- CMC and C/C would be subjected to high mechanical loading
- CMC and C/C components will be characterized by cooling ducts and notches in the case of active cooling
- Experience gained in aerospace field with composite materials indicate that a damage tolerance design approach is the most suited for quasi-brittle materials with multiple damage and failure modes
- Knowledge of damage phenomena, experimental approaches and numerical modelling for progressive damage accumulation and failure will play a fundamental role

## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

- CMC and C/C are already used as primary structural components in automotive brake disk

Structural roles are not critical in Multi-discs aircraft brakes stator and rotor discs pressed ➡ Loads mainly in the disc plane

In automotive disks material strength is fully exploited in a critical primary structure

C/C formula 1 disk

CMC sport cars disk

- High out-of-plane loading
- Geometry characterized by ventilation holes and notches

⬇

Severe mechanical load conditions (in-plane + bending + transverse shear)

Stress concentrations at notches



## CMC AND CARBON/CARBON STRUCTURAL COMPOMENTS

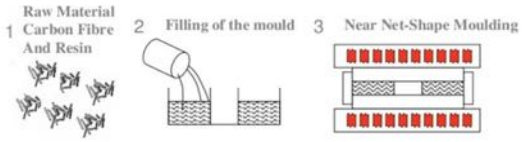
- Critical mechanical loading motivated a significant research effort for mechanical characterization, material modelling and structural analyses of C/C and C/SiC components

- Politecnico di Milano, BSCCB, Brembo and Petroceramics co-operated to characterize and model several inelastic response of C/SiC and C/C materials

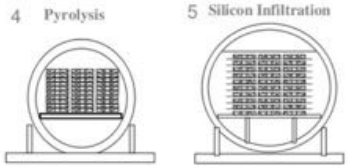
- An highlight of the most significant results will be provided in this presentation

## MULTI-SCALE MODELLING OF DAMAGE IN CMC COMPONENTS

- Short fiber reinforced C/SiC produced by LSI used for high performance car brake disks

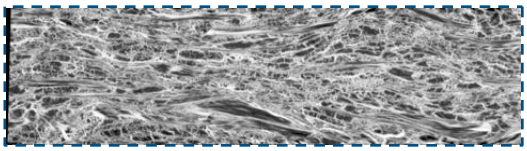


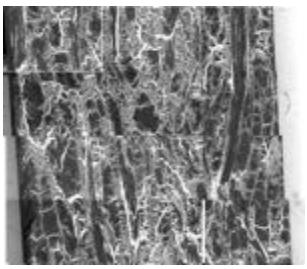

molding of polymeric precursor




Pyrolysis and LSI

- isotropic matrix reinforced by cylindrical bundles (but very irregular microstructures)
- Anisotropy induced by packing of fibers

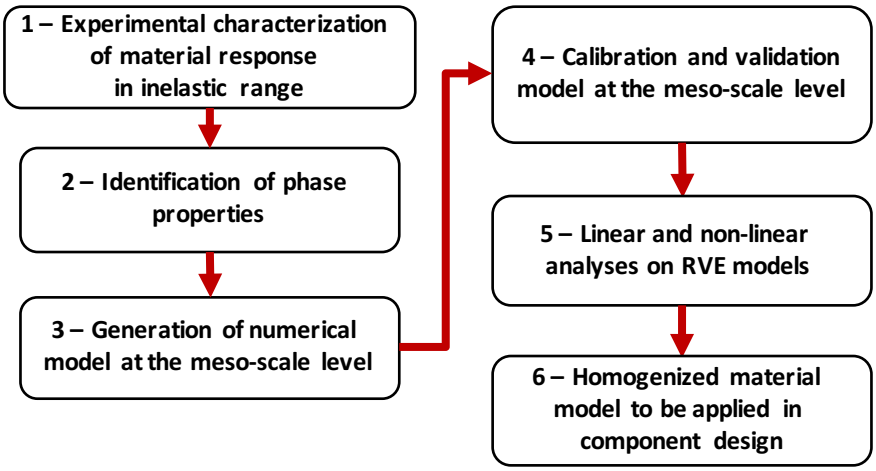






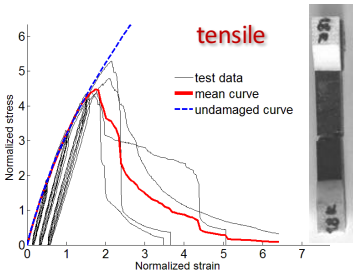
## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

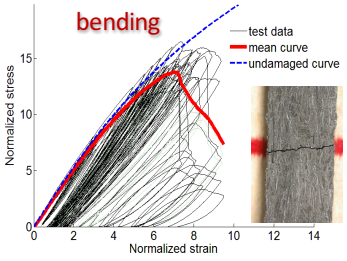
- Multi-scale approach



## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

- Experimental characterization: accumulation of permanent strain (pseudo-plasticity), damage and macroscopic cracks
- Loading-unloading cycles to measure permanent strains in tensile and bending tests




Permanent strain and damage evaluation at each cycle → evaluation of non-linear effects due to permanent strain only (blue curves)



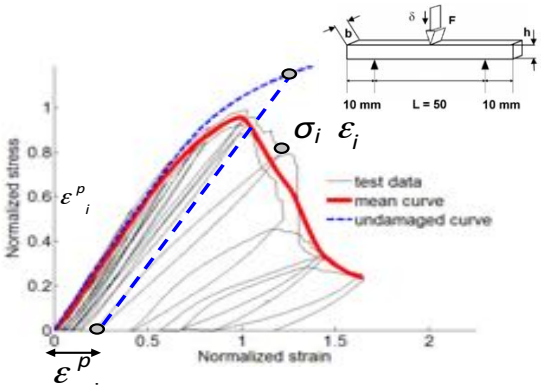
## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

- Phase identification: bending test on burnt specimens
- Matrix includes voids, microcracks, unreacted Si and C
- Properties are very different from nominal SiC and are unknown

C/SiC Specimens treated in an oven at 800 °C for 10 hours

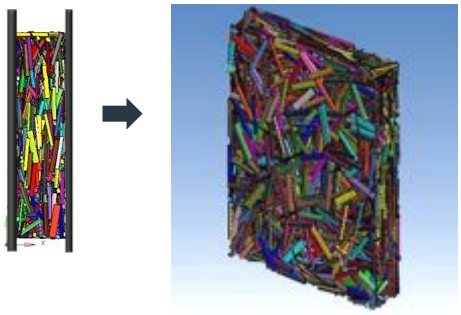
Elimination of carbon content, characterization of matrix phase in the final material

- Fiber properties identified by means of long fiber reinforced samples

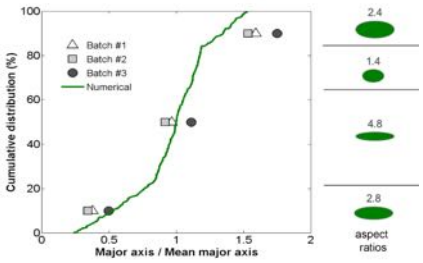


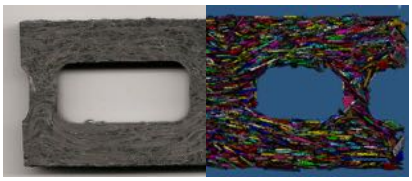
## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

❑ Model Generation: simulation of packing to create a FE mesh



- Orientation distribution is in qualitative agreement with experimental evidence



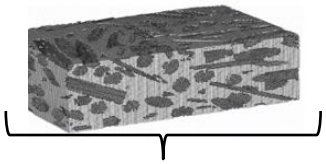
- Any size/shape distribution of fiber bundles can be considered
- Structual details can also be modeled



## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

❑ Meso-scale models: material models for the phases

| | | | |
|---|---|---|---|
| MATRIX | isotropic | Elastic-plastic (Drucker-Prager) material + damage | Material properties identified by using burnt specimens (Airoldi et al. 2012/2013) |
| CARBON FIBER BUNDLES | Transversely isotropic | Elastic | Material properties from identification process (Airoldi et al. 2012/2013) |



16 mm

Different models created

Linear analyses

➡ Identification of elastic properties

Non-linear analyses

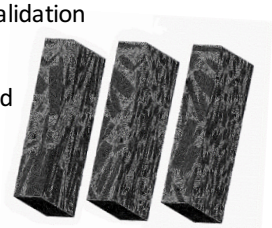
➡ Damage/failure criteria

## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

❑ Identification of elastic-properties

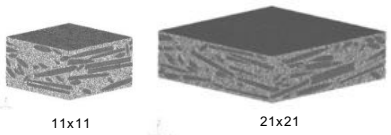
Standard CMC materials with short fibers used for validation

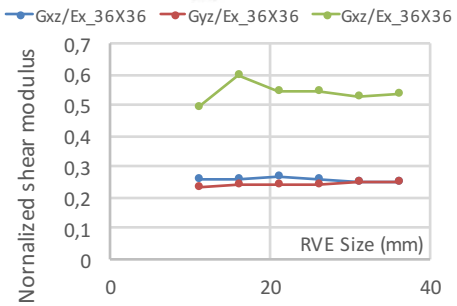
Three different meshes generated by different packing simulations



| E Model 1 | E Model 2 | E Model 3 | STD |
|---|---|---|---|
| E Ave Test | E Ave Test | E Ave Test | E Test |
| 98.2 % | 107.1% | 109.6 % | 16.0 % |

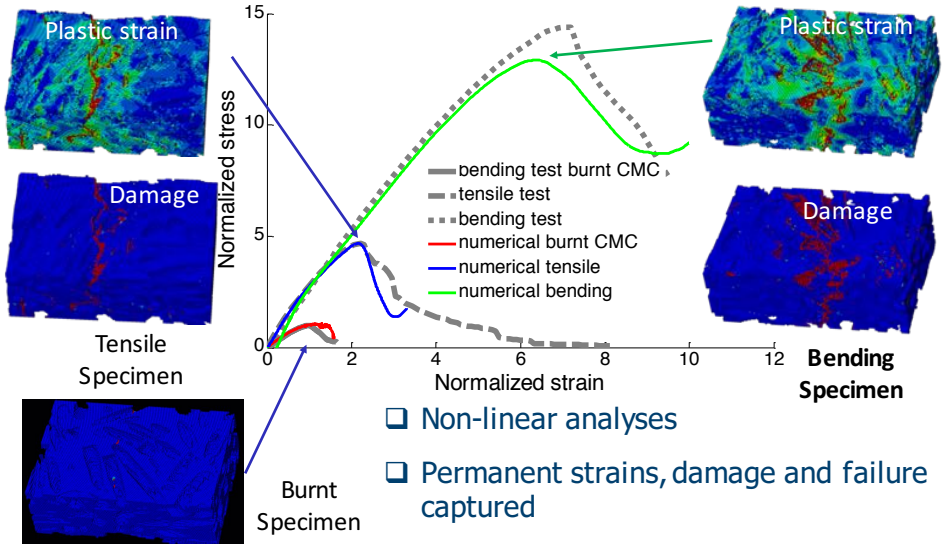
Analyses on RVE for homogenized material model






## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS




❑ Non-linear analyses

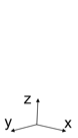
❑ Permanent strains, damage and failure captured

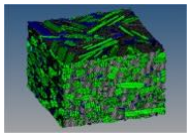
## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

- Non-linear RVE analyses

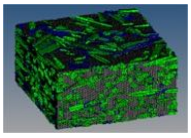
9 virtual tests performed in tension, compression, shear

Tsai-Wu type criterion developed and implemented in disk analysis

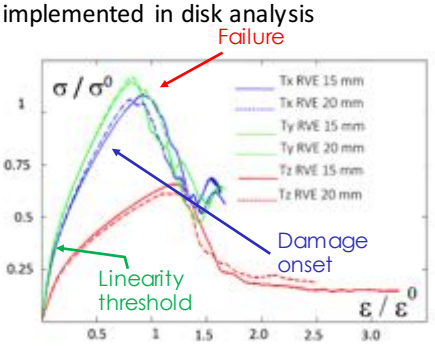


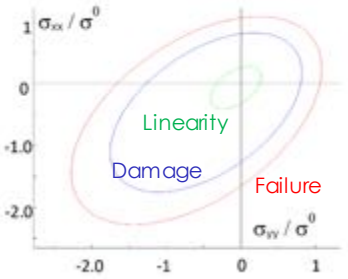
15 x 15 x 10 $mm^3$ (1.5 M elements)



20 x 20 x 10 $mm^3$ (2.7 M elements)




Tensile tests (2 RVE sizes)




Damage/Failure envelope

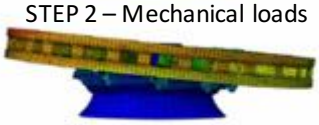


## MULTI-SCALE MODELLING OF DAMAGE IN C/SI C COMPONENTS

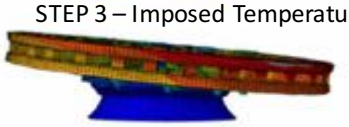
- Application to thermo-mechanical analysis of the structural part

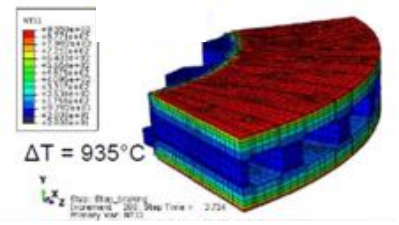
STEP 1 - Pretension

STEP 2 – Mechanical loads

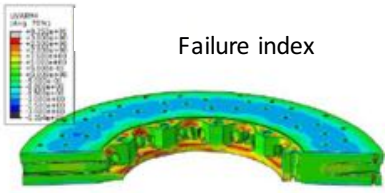


STEP 3 – Imposed Temperature





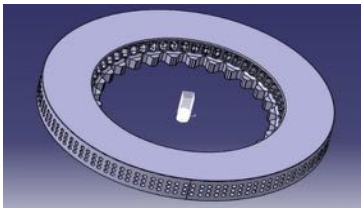

Temperature Map

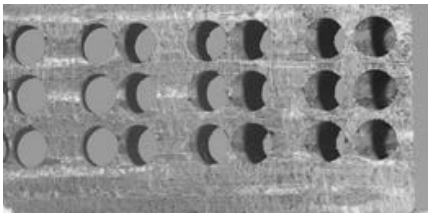


Failure index

## MODELLING OF DELAMINATION IN C/C LAMINATES

❑ Characteristics of C/C components





Pre-forms are made of thick (>1 mm) unidirectional fibrous layers, needled and subjected to rapid CVI processes

Material properties strongly depends on porosity (macro-porosity and defects can be seen at low magnifications)

Very dense pattern of ventilation holes

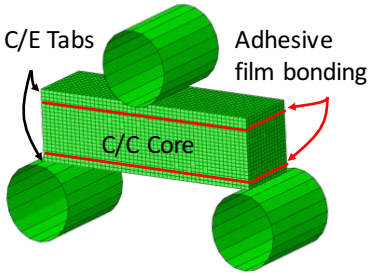
Delamination is a critical failure mode



## MODELLING OF DELAMINATION IN C/C LAMINATES

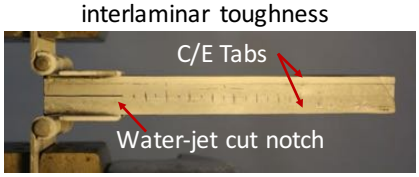
❑ Experimental approach to study C/C delamination

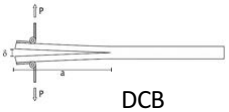
Lamina failure must be avoided, Carbon/Epoxy tabs are bonded to avoid tensile compressive failure and promote pure delamination



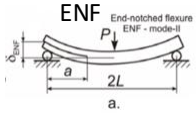

3-pt bending specimen (no pre-crack)

Pre-cracked sperimens to measure interlaminar toughness



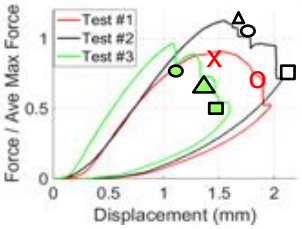



DCB



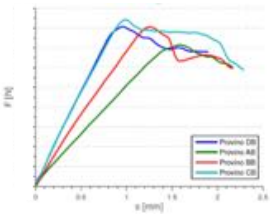
## MODELLING OF DELAMINATION IN C/C LAMINATES

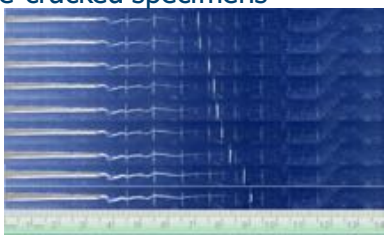
- Unstable crack propagation in 3 pt bending test





- Stable crack propagation in pre-cracked specimens

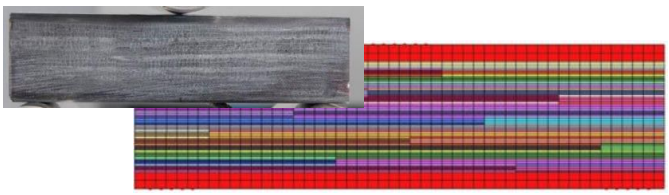






## MODELLING OF DELAMINATION IN C/C LAMINATES

- Modelling approach developed at Dept. of Aerospace Science and Technology

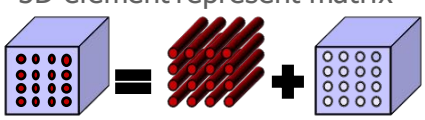


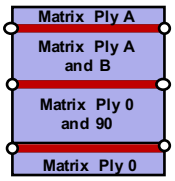
Detailed model

Very complex lamination sequence due to technological process

- Hybrid/bi-phasic approach

2D element (shell) reprent fibres,
3D element represent matrix



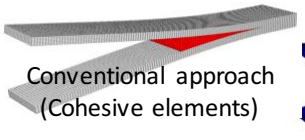



Inside matrix elements a constitutive law (cohesive model) is introduced to model delamination damage

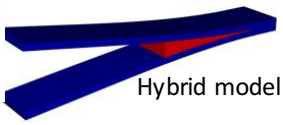
## MODELLING OF DELAMINATION IN C/C LAMINATES

- Very powerful approach to efficiently model multiple delamination scenations

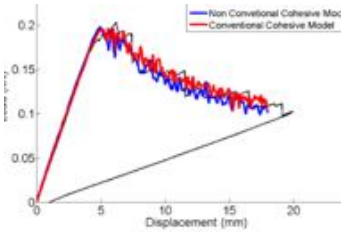
(Cfr. Results with polymer matrix composites Airoldi, Baldi, Sala et al. 2007-2013 )



Conventional approach (Cohesive elements)

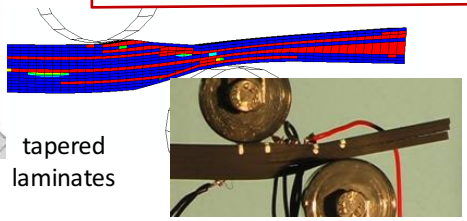


Hybrid model




1 order of magnitude gain in computational time

curved laminates

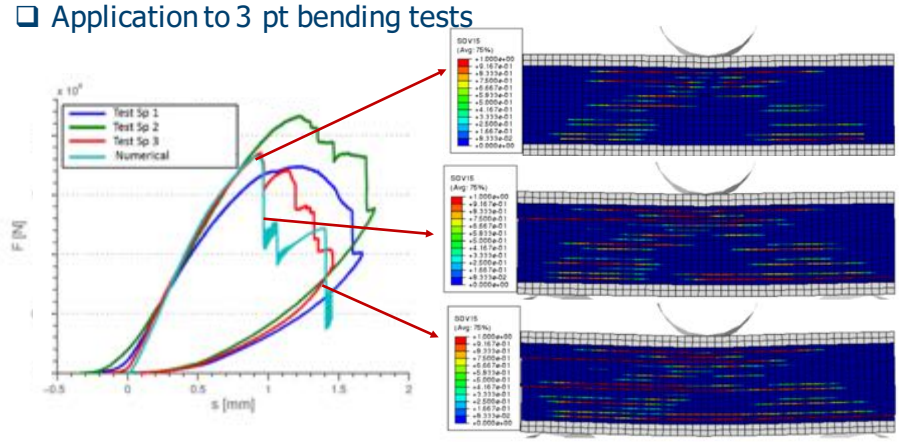


tapered laminates



## MODELLING OF DELAMINATION IN C/C LAMINATES

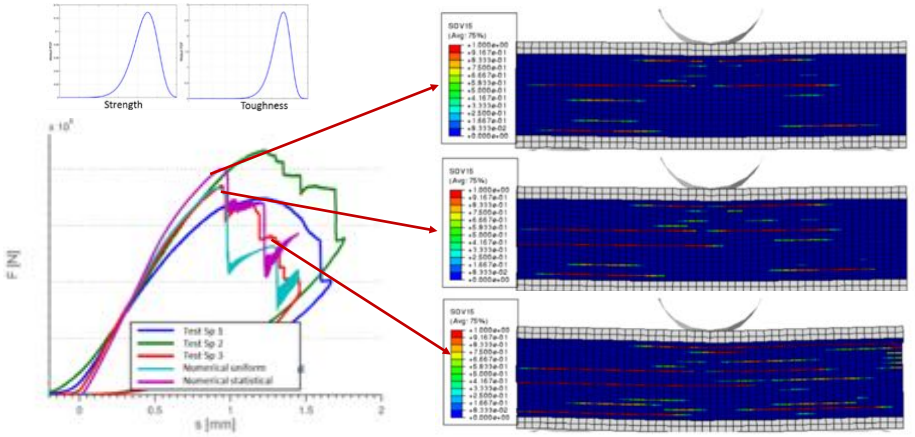
- Application to 3 pt bending tests




Model calibrated by using pre-cracked tests (DCB and ENF)
Capability of modelling multiple delamination scenarios
Damage overestimated in Post-failure response

## MODELLING OF DELAMINATION IN C/C LAMINATES

- Introduction of statistical distribution of interlaminar properties



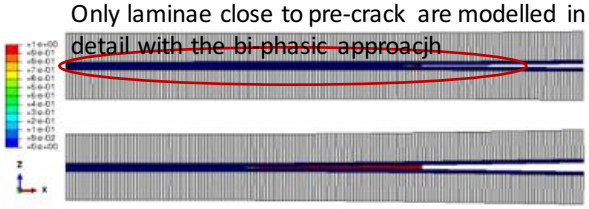

Improvement of post-failure response
Reduction of diffused damage

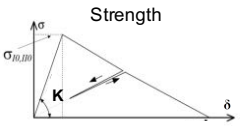


## MODELLING OF DELAMINATION IN C/C LAMINATES

- Model calibration by means of pre-cracked DCB and ENF test

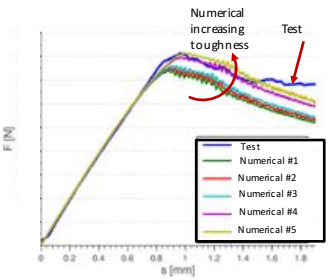
Only laminae close to pre-crack are modelled in detail with the bi-phasic approacjh






Area = toughness ($G_c$)

Cohesive law in each matrix element

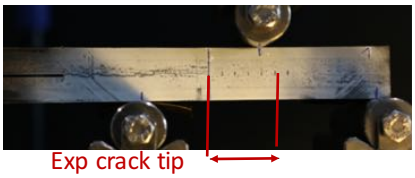



Numerical-experimental correlation used to identify interlaminar toughness in this non-conventional test (non-uniform specimem)

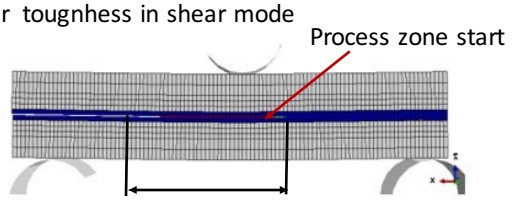
## MODELLING OF DELAMINATION IN C/C LAMINATES

- Model calibration by means of pre-cracked DCB and ENF test

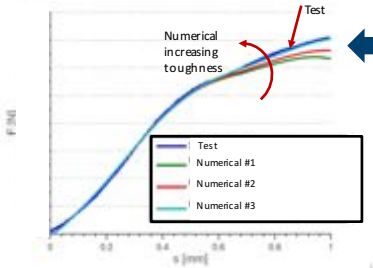
ENF tests measures interlaminar toughness in shear mode



Exp crack tip

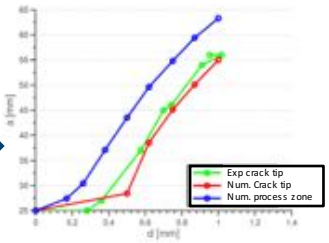



Num Crack tip




Force vs. disp correlation

Crack tip advancement correlation

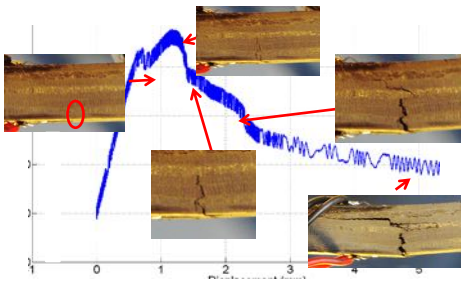




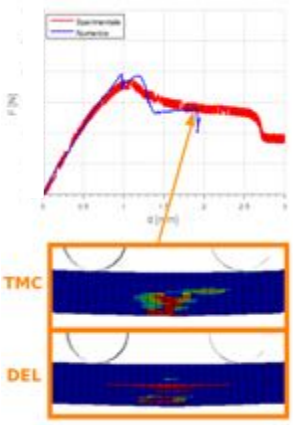

## MODELLING OF DELAMINATION IN C/C LAMINATES

- On going work for C/C components

modelling of lamina damage (transverse matrix cracking )in the approach



4 pt bending test with development of intralaminar crack and subsequent delamination




Preliminary numerical results

## CONCLUSIONS

- Damage onset, accumulation and failure have been experimentally investigated and numerically modelled
- Specific experimental approaches, such as burnt CMC specimens and Carbon/Epoxy reinforced C/C specimens, have been assessed to address some critical issues in the characterization of materials
- The developed numerical approaches (at different scale levels) represent promising tools to design damage tolerant hot structures in CMC and C/C materials
- Modelling of interfaces by means of cohesive zone models is the appropriate approach to numerically address the structural integrity of external protective barriers or ablative additional layers applied to the hot structures




SECOND SYMPOSIUM ON HYPERSONIC FLIGHT – C.E.S.M.A. 30 GIUGNO/1 LUGLIO 2016

# NUMERICAL APPROACHES TO DAMAGE TOLERANCE OF CARBOCERAMICS AND CARBON/CARBON MATERIALS

Alessandro Airoldi[1]. Giuseppe Sala[1]. Paolo Iavarone[2]. Raffaello Passoni[3]. Massimiliano Valle[4]

*Thank you for your kind attention*