Issues for the life prediction of Ceramic Matrix Composite components

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Summary

- CMCs are of interest to thermostructural applications.
- They were developed initially for military and aerospace applications.
- Effort on CMCs in France started in the seventies
- They have now a high level of technological development.
- The issues have moved from processing methods and basic characteristics to issues relative to resistance to high temperatures and aggressive environments, life of material and components, predictive models and simulation.
- Predictions and control of life are fundamental issues for safe introduction and reliable use of Ceramic Matrix Composites (CMCs) in industrial systems running at high temperature or in aggressive environments.

Summary

- Applications

- Some exceptional properties of CMCs:

  Features of fast fracture
  Features of delayed fracture at high temperature

- Significance of microstructure/properties relationships

- Multiscale Modeling for lifetime prediction and composite design by tailoring properties to service conditions

APPLICATIONS

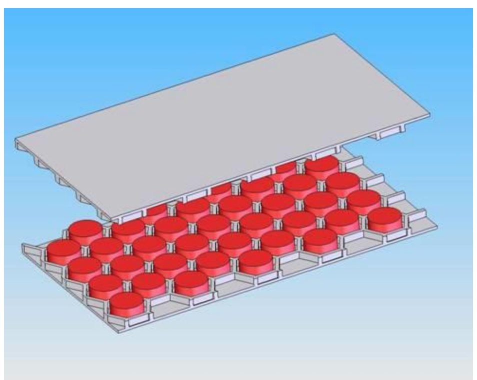
Ceramic Matrix Composites (CMC) : FIBRES + *Interphase* + MATRIX

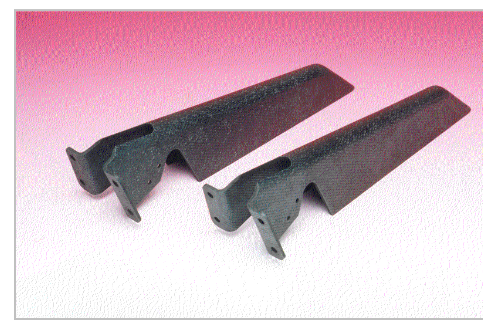
(SiC, C) (PyC, BN) (SiC, C)

⇓

High temperature structural applications

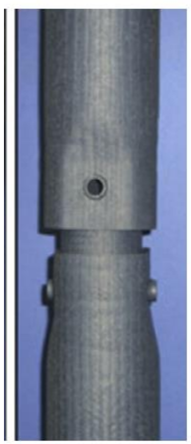
- Space and Defence
- Aeronautical applications
- Nuclear reactors



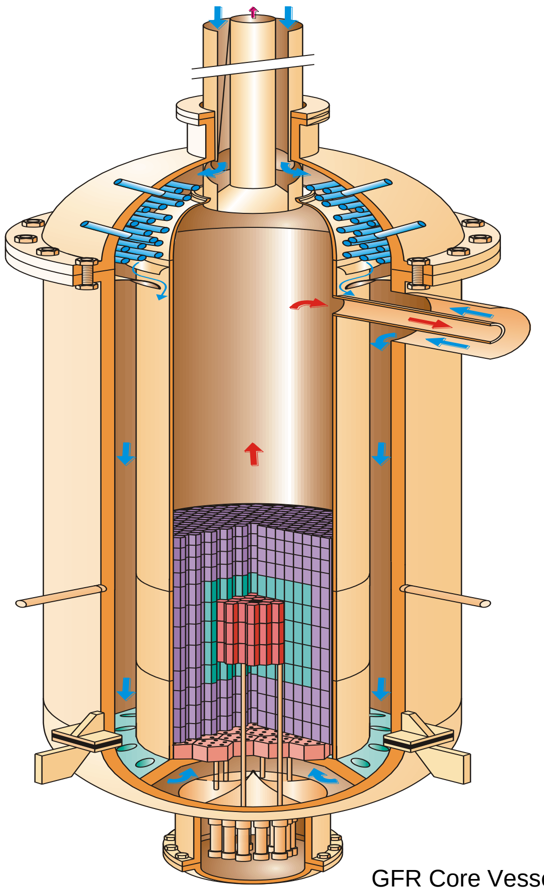


Issue : lifetime control and prediction for long term applications

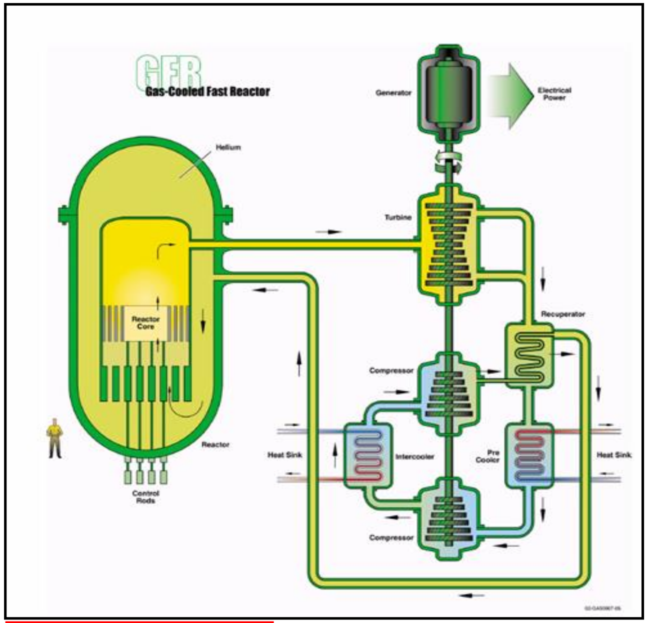
NUCLEAR POWER PLANTS



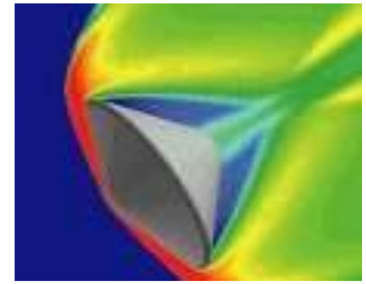
Fuel cladding
Control rods
(SiC/SiC)



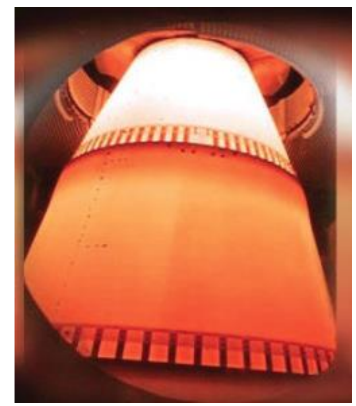
GFR Core Vessel



Gas Fast Reactor



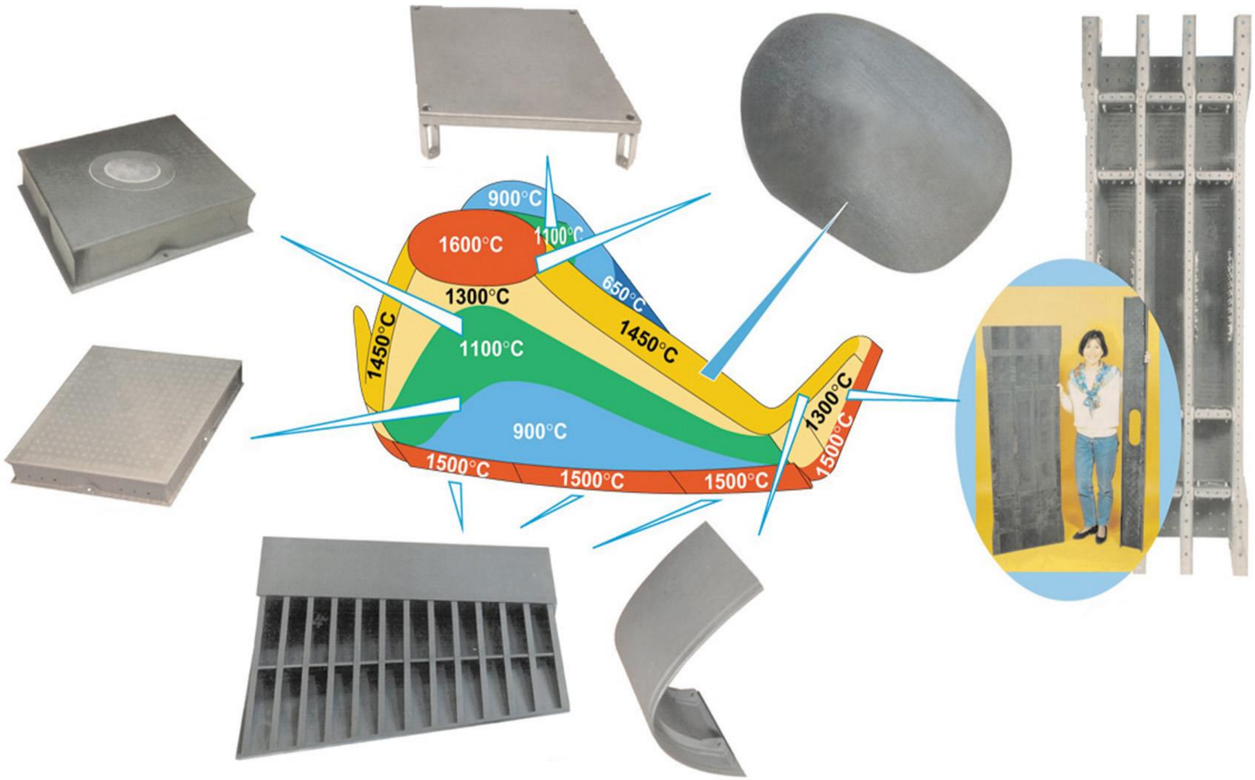
SPACE CRAFT THERMAL PROTECTION



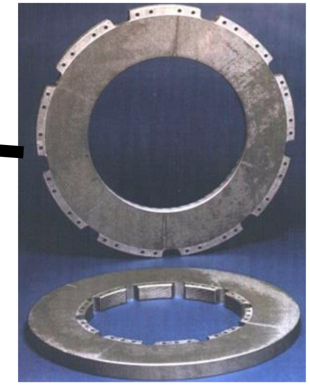
PROPULSION

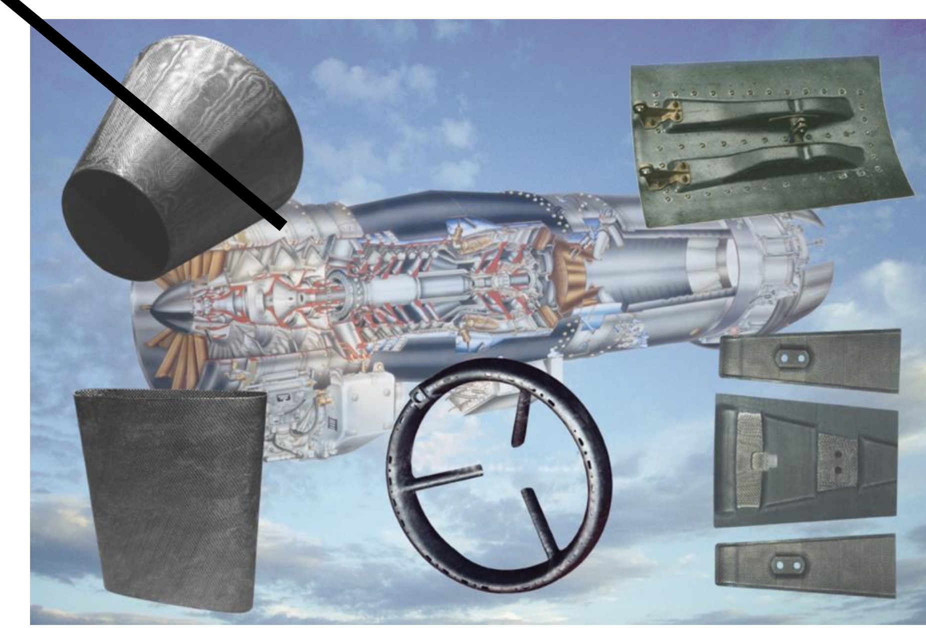
ARIANE LAUNCHER

HERMES EUROPEAN SPACE SHUTTLE PROJECT
Thermal protection components

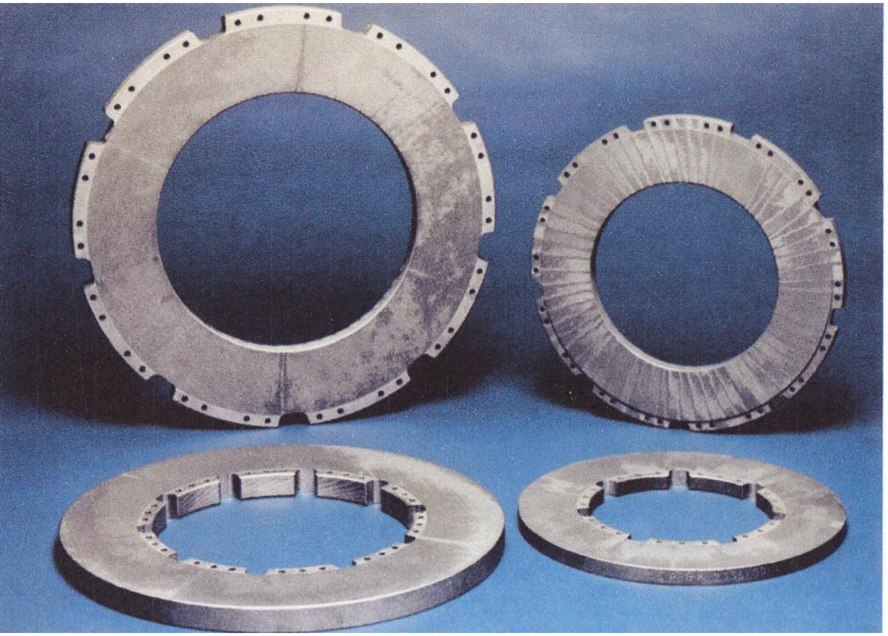


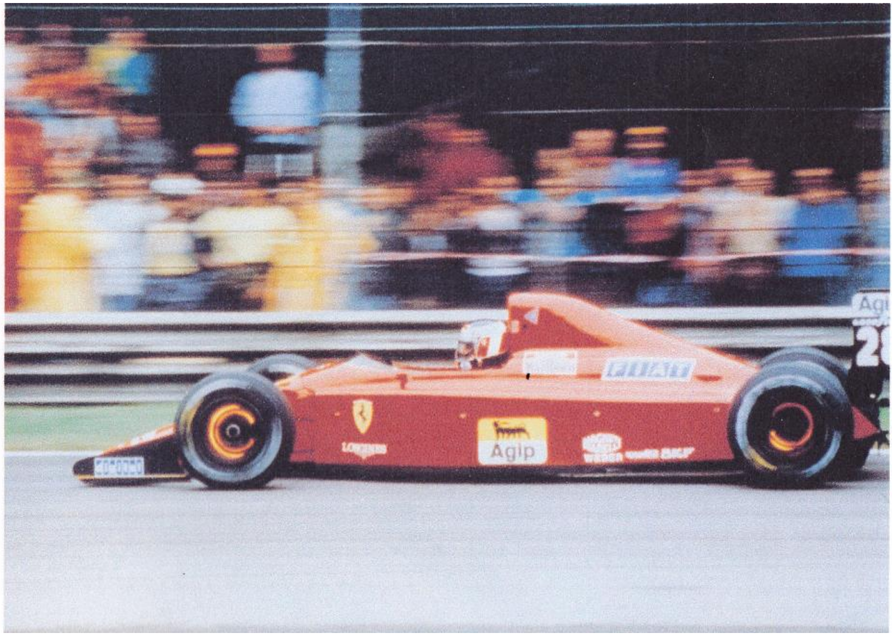
AERONAUTICAL APPLICATIONS





C/C FORMULA 1 BREAKS





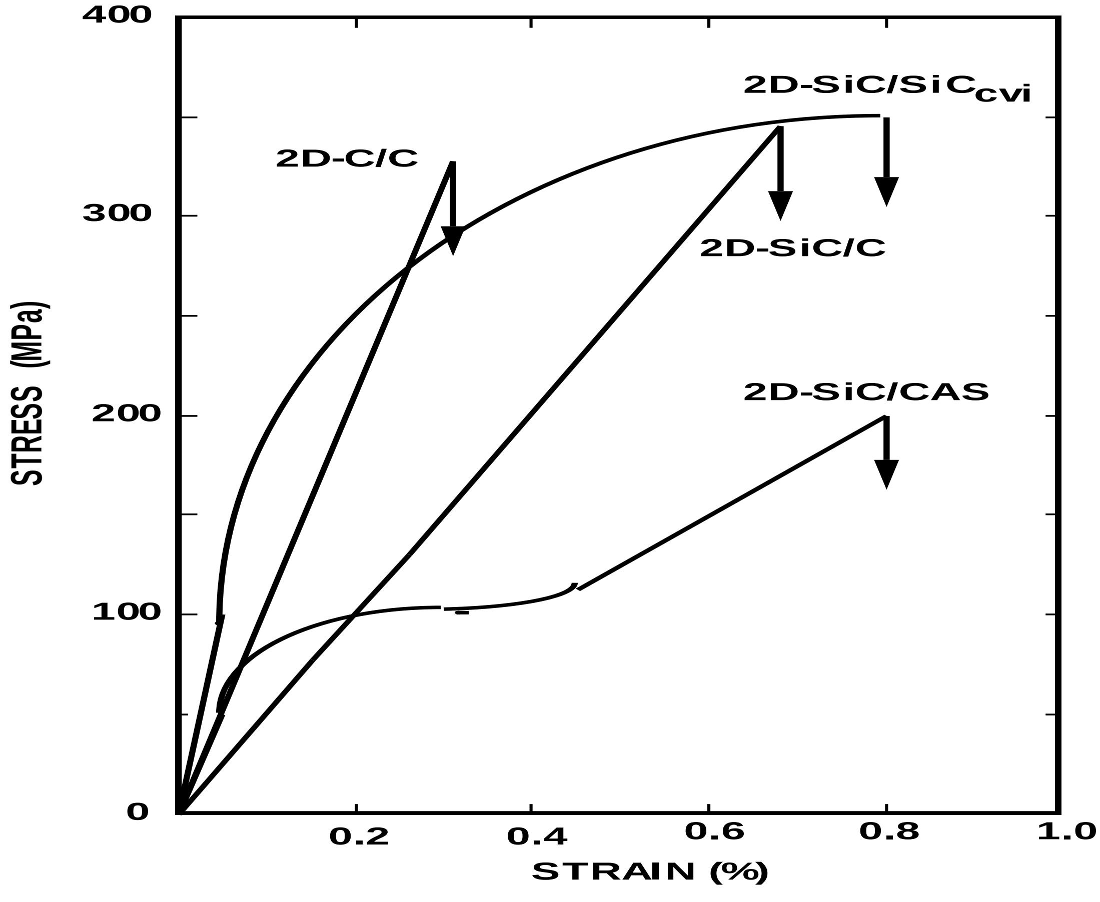
CERAMIC MATRIX COMPOSITES

CMC continuous fiber reinforced ceramics display remarkable properties

- **resistance to high temperature**
- **resistance to high temperature fatigue**
- **versatile stiffness**
- **damage tolerance**
- **crack arrest capability**
- **decreased flaw sensitivity**
- **quite infinite toughness/notch insensitivity**
- **reliability**
- **versatility**

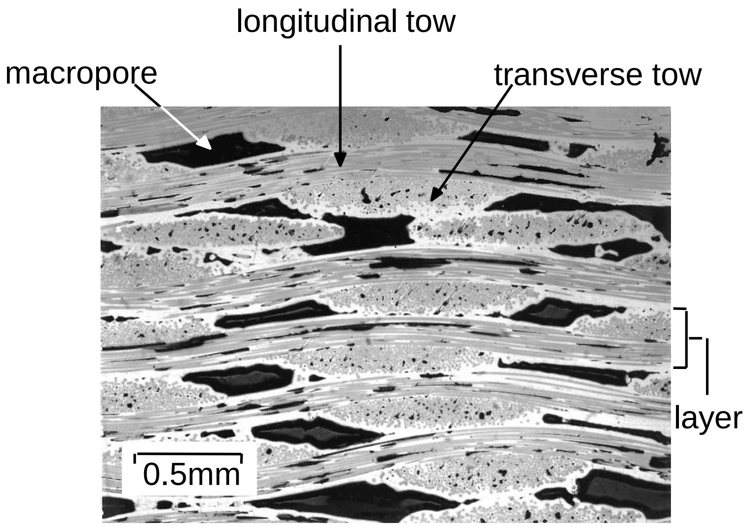
VERSATILITY of CMCs

Tensile behavior: influence of Young's modulus contrast

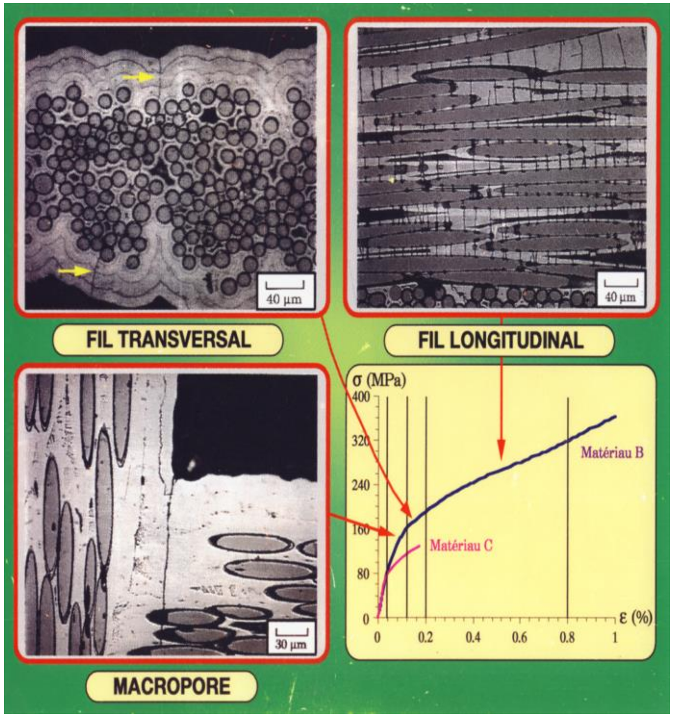


(after A. G. Evans)

Microstructure – damage – behavior relationship



2D woven SiC/SiC microstructure

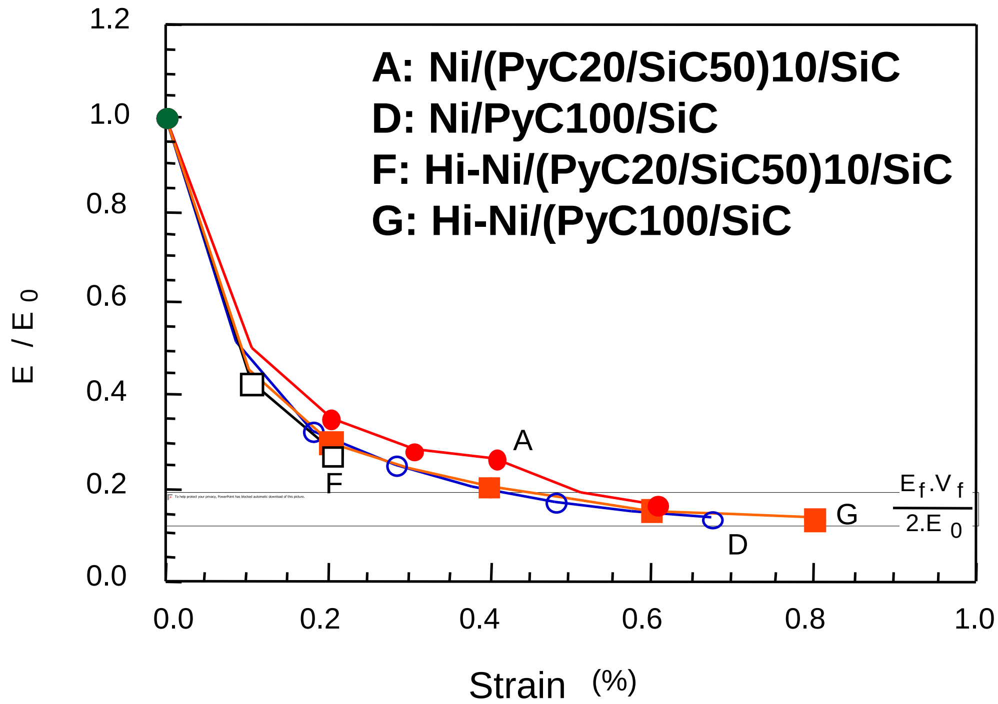


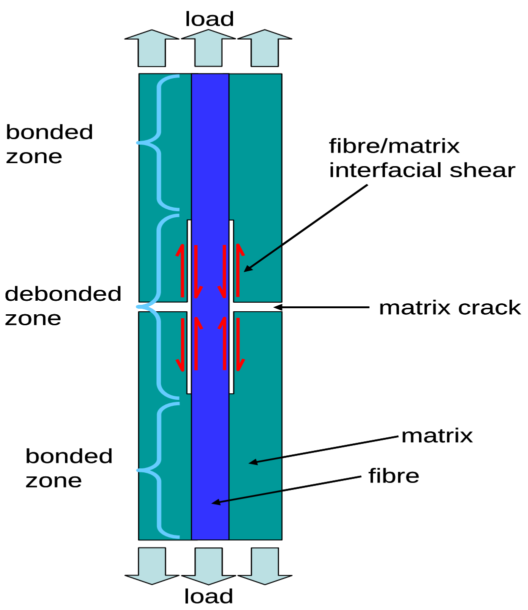
Matrix damage and tensile behavior

(Guillaumat, Lamon, 1993)

DAMAGE: Load transfer from matrix to fibers during matrix damage in 2D woven SiC/SiC

RELATIVE YOUNG'S MODULUS





TOP DOWN PROCESS

(Bertrand, Pailler, Lamon, 2001)

Tensile strength: tow – controlled fracture of 2D composite

Tensile strength of composite

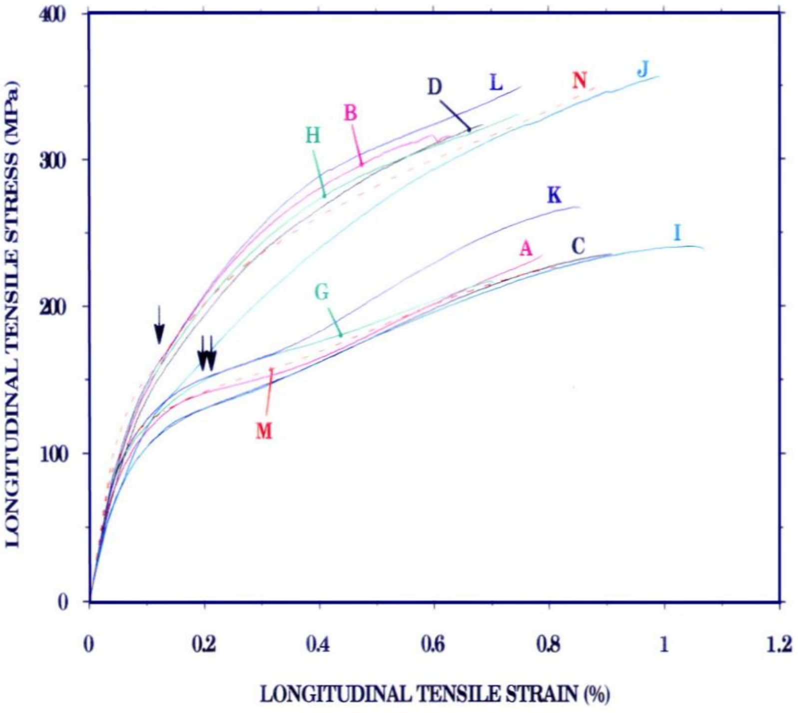
$$\sigma_{TS} = V_L \, \sigma_{tow}$$

Tensile strength of tow

$$\sigma_{tow} = \frac{F}{N_t (1 - \alpha_C) \Pi R_f^2}$$

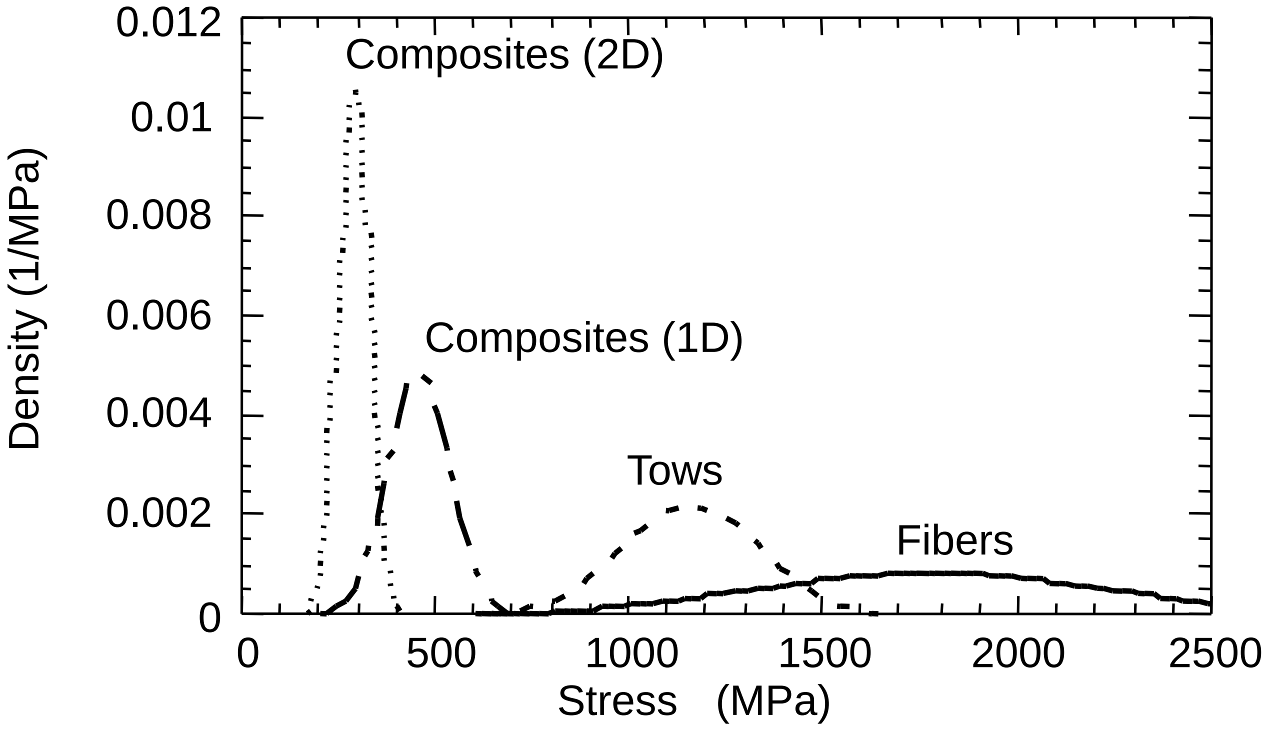
Predictions for 2D Nicalon / SiC composites

$N_t = 500$
$\alpha_C = 0.17$
$V_L \approx 0.2$
$R_f = 7.5\ \mu m$



	Minimum Tow strength F(N)	Composite strength σ_{TS} (MPa)
ELS	90	245
LLS	70	190
RLLS (β_r = 0.35)	40	109
RLLS (β_r = 1)	25	68

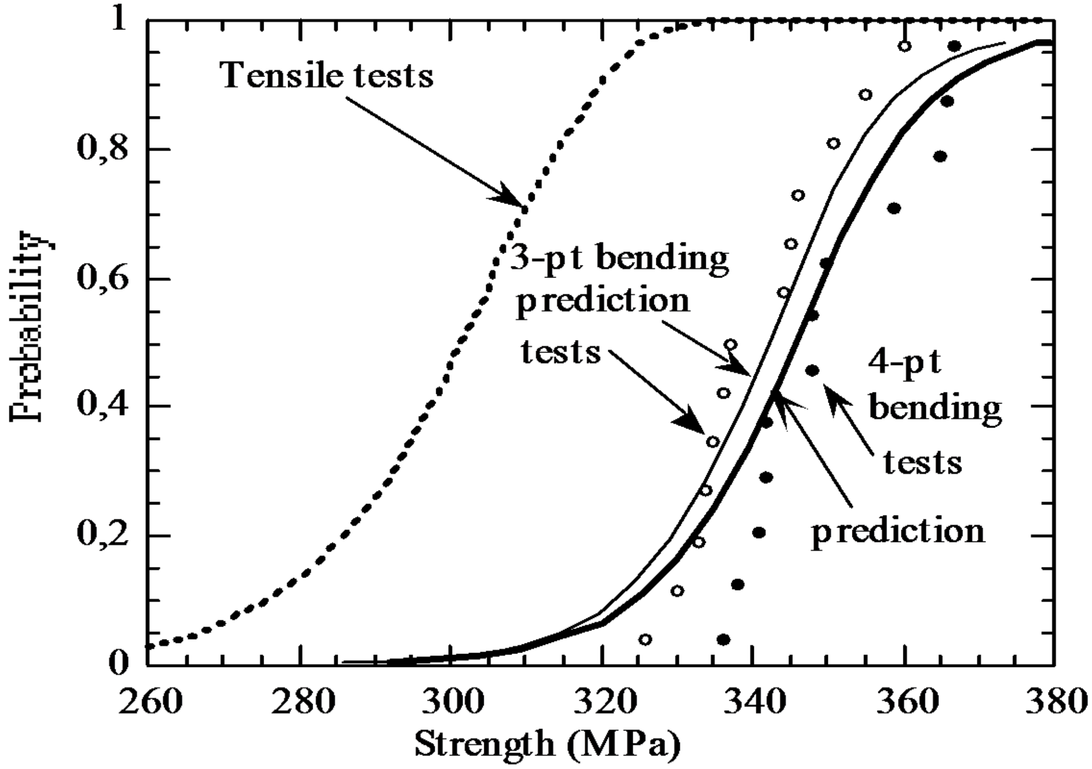
Reliability: Ultimate failure of CMCs: from single filaments to woven composites



Strength density functions for SiC fibers (NLM 202), SiC fiber tows, SiC/SiC (1D) minicomposites and 2D SiC/SiC composites

(Calard, Lamon, 2002)

Reliability: Ultimate failure of CMCs: statistical distributions of failure strengths



limited effects of stress-state

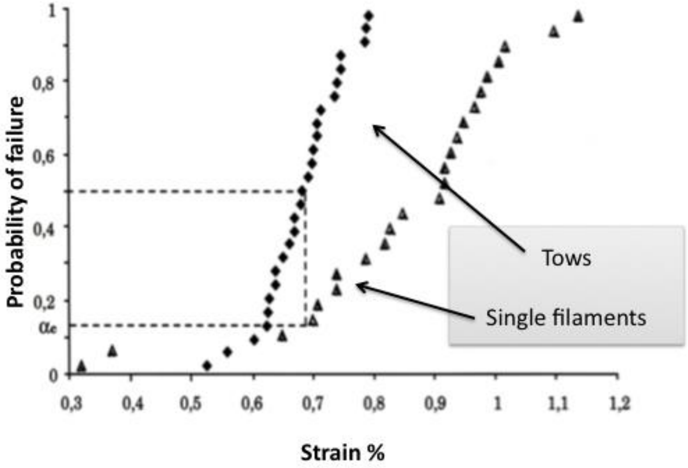
$\sigma_{3p} / \sigma_R \approx 1.15$

(Calard, Lamon, 2002)

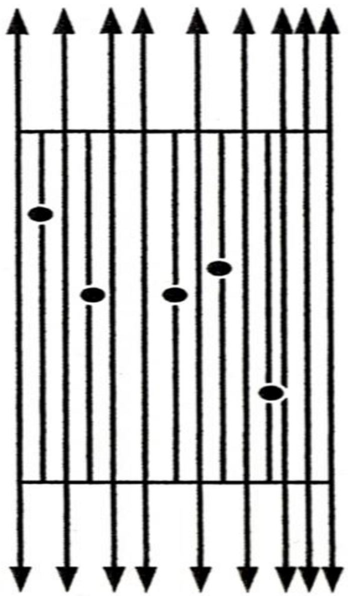
Multiscale modeling of tensile behavior

Ultimate failure of filaments and multifilament tows

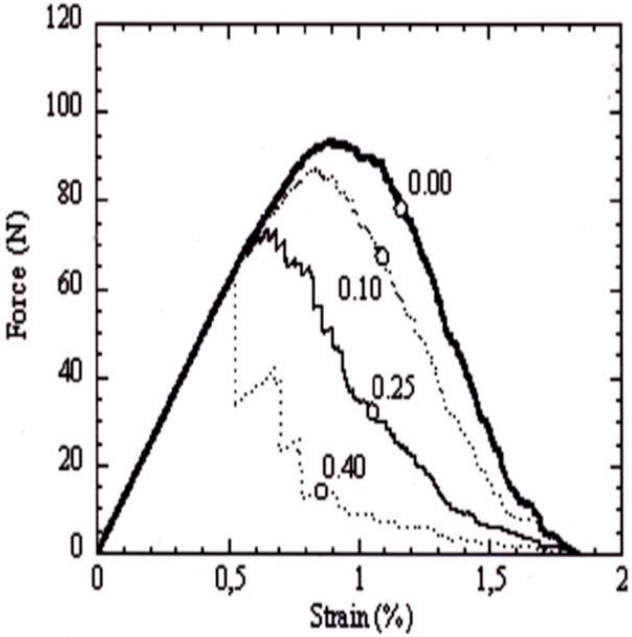
Statistical distribution



Damage mode

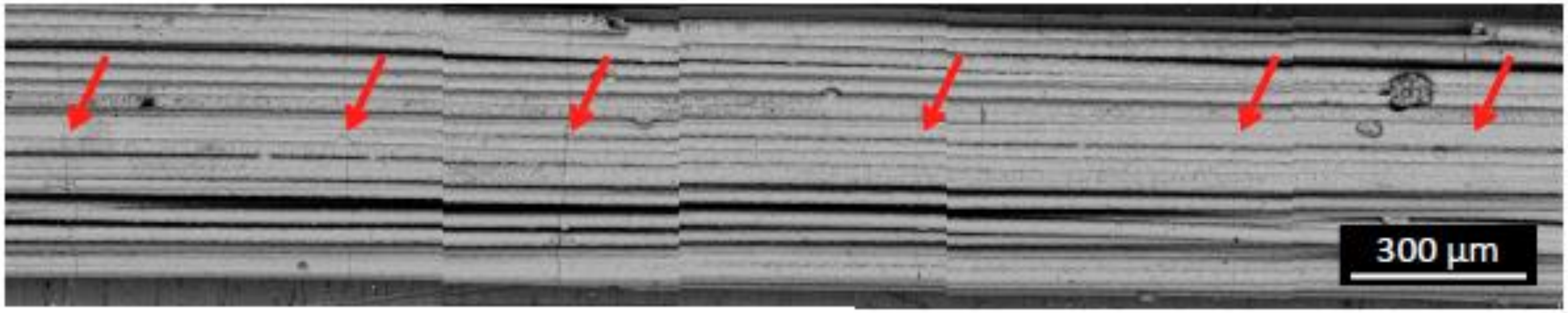


Tensile behavior

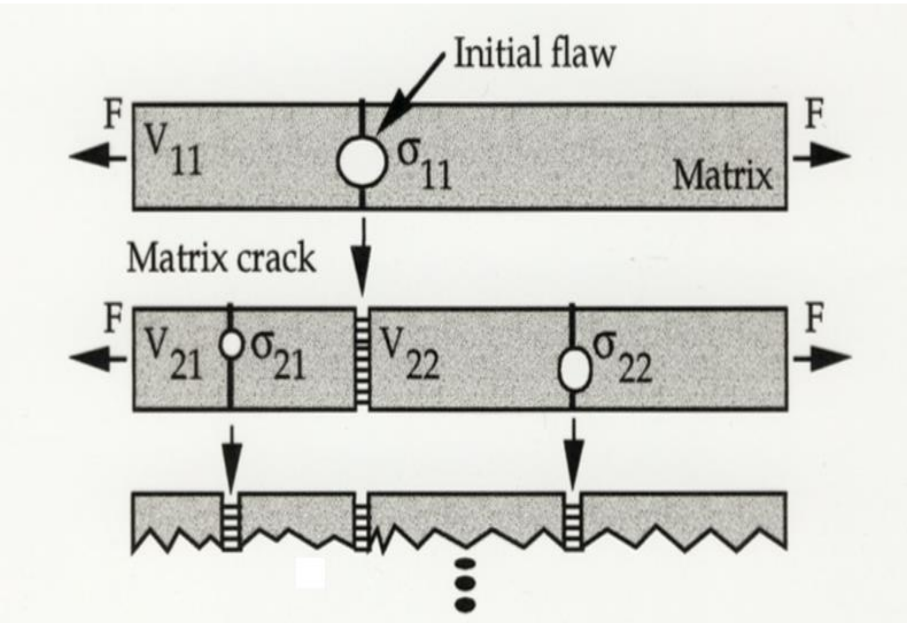


[Calard, Lamon, 1996]

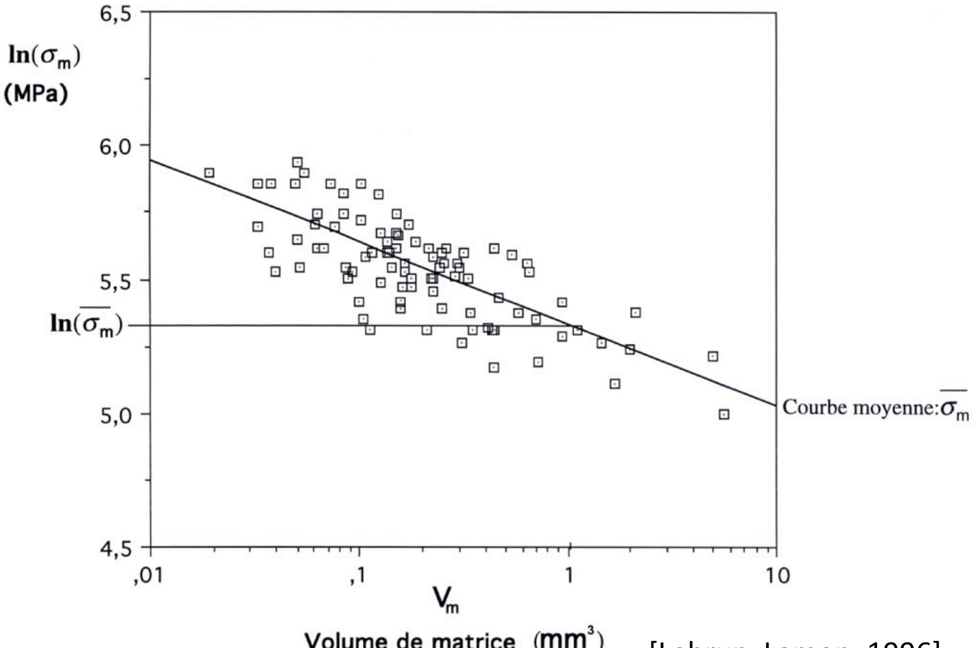
Matrix fragmentation in CMCs



Flaw-induced stochastic process

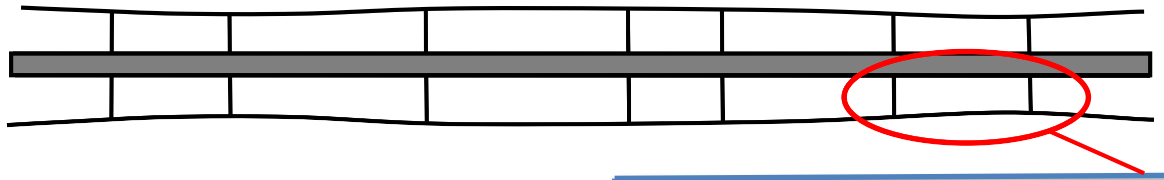


[Calard, Lamon, 1998]



[Lebrun, Lamon, 1996]

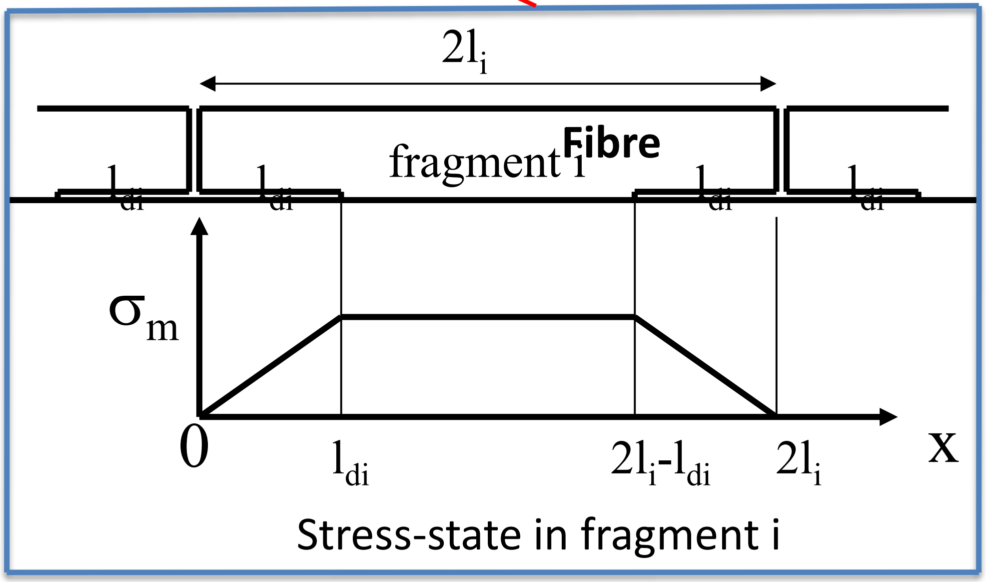
Matrix damage: Fragment dichotomy based model



Strength data have Weibulll distribution

$$P_{rup}^{V_i} = 1 - \exp\left\{ -\frac{1}{V_0} \int_{V_i} \left[\frac{\sigma}{\sigma_0} \right]^m dV \right\}$$

$$V_i = S \cdot l_i$$

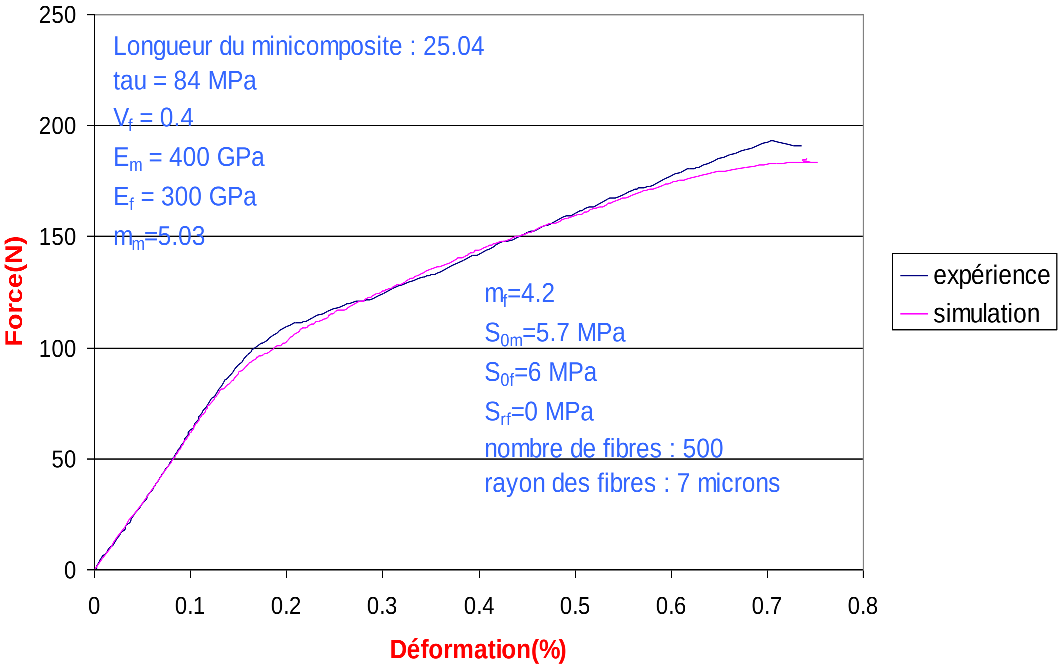


Fragment volume (equivalent to length l_i) is a statistical variable such as

$$P_{(x)} = \frac{x - l_d}{l_i - 2l_d}$$

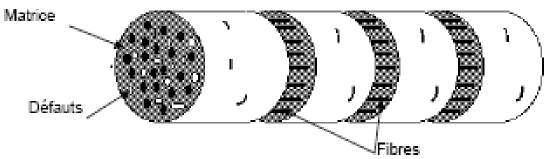
(Lissart, Lamon, 1997, 2009, 2010)

Prediction of composite tensile behavior

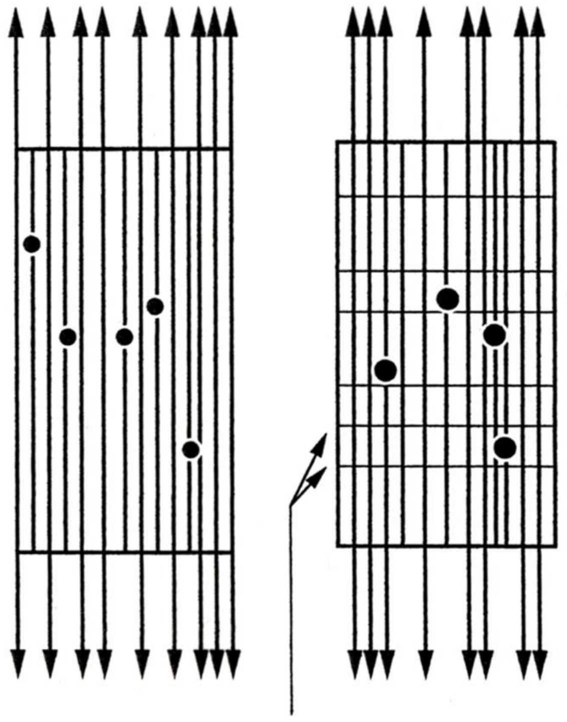


[Pailler, Lamon, 2004]

Matrix damage mode



Tow damage mode



Damage tolerance and notch sensitivity

Resistance to crack propagation

2D woven SiC/SiC fabricated
By polymer conversion process
(Kagawa, Goto (1997))

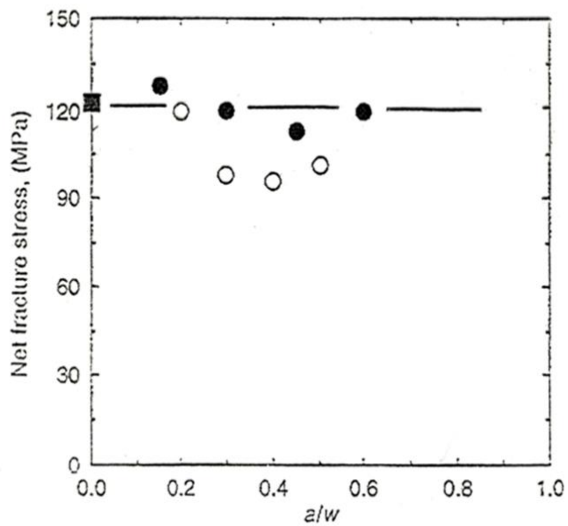
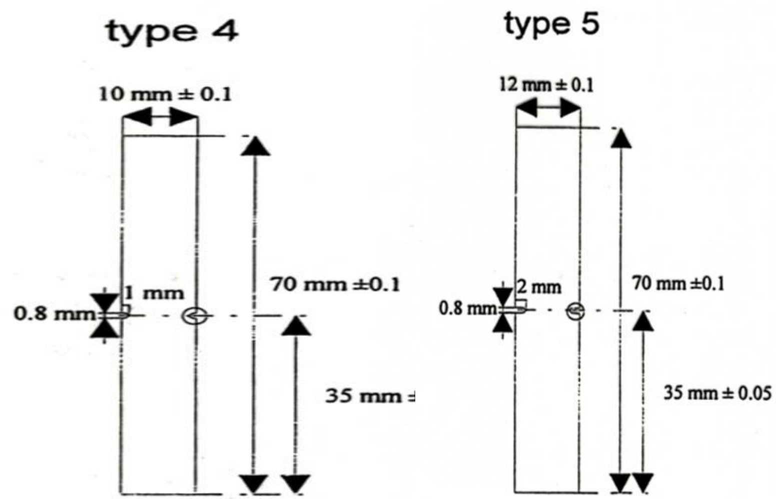
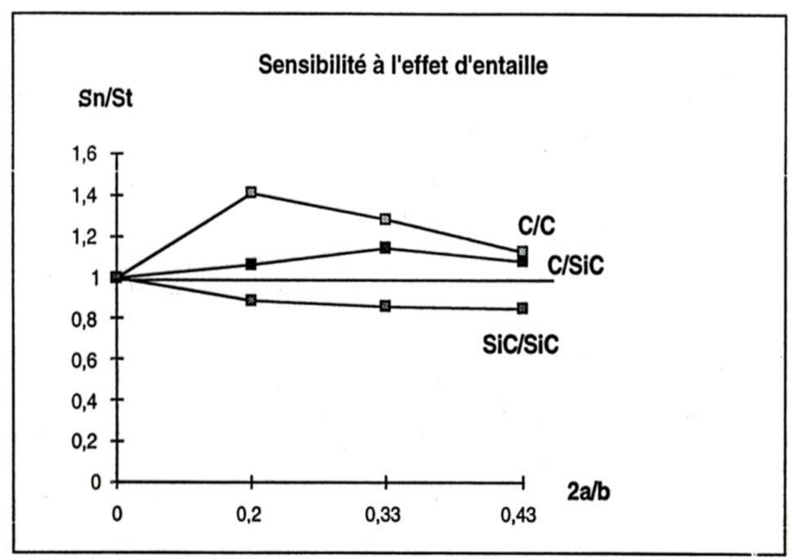


Figure 7 Plots of the net stress, σ_c^{net}, versus a/w of, (■) unnotched specimens, (○) SEN specimen, and (●) DEN specimen.





C/C and C/SiC are notch insensitive
SiC/SiC may be notch insensitive

Notch sensitivity

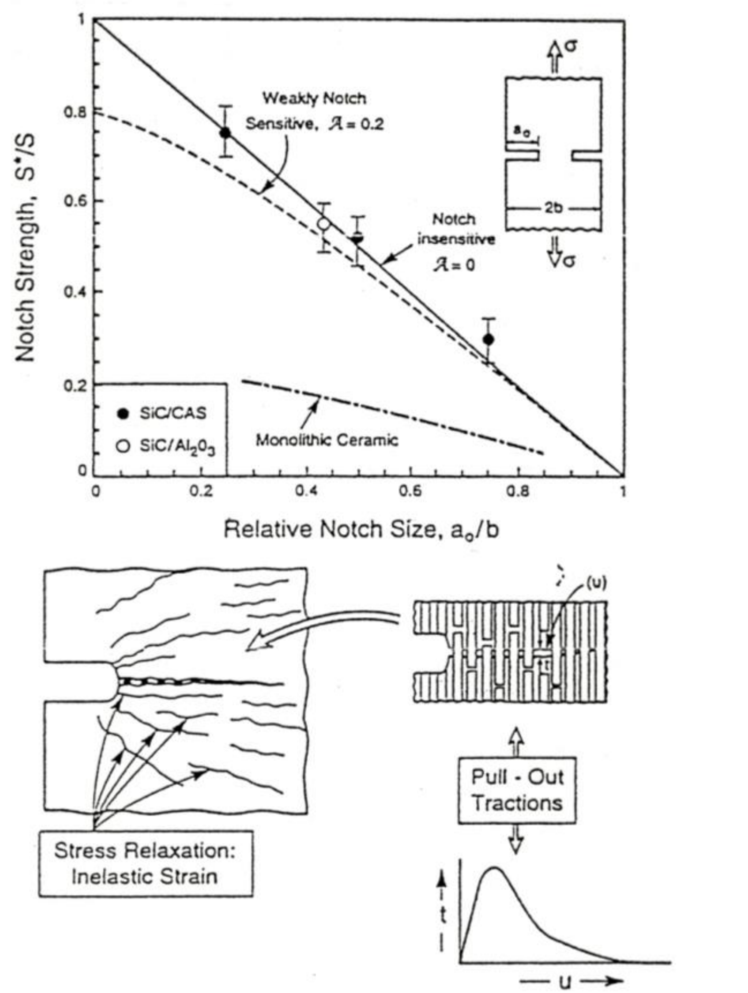


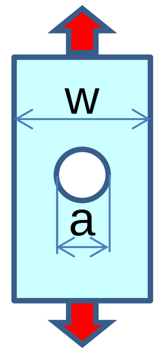
Fig. 5. The notch insensitive behaviour found for SiC/CAS and SiC/Al₂O₃. The inset shows the pull-out mechanism.

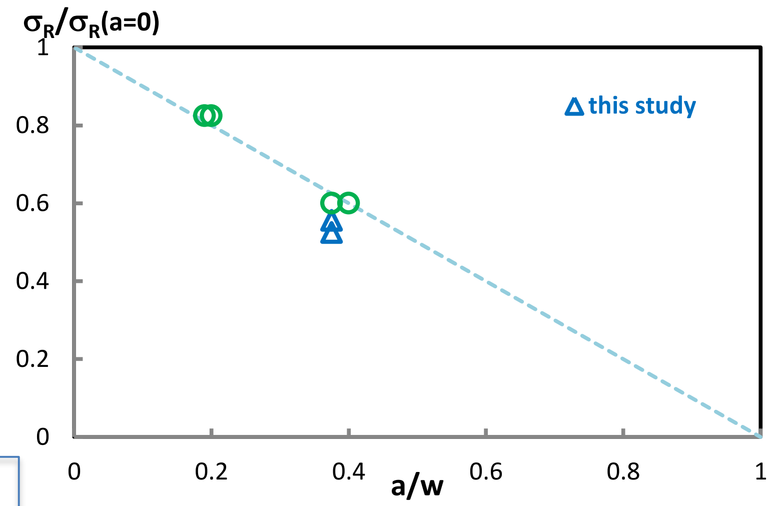
A. G. Evans (1997)

Damage sensitivity

Post impact tensile strength

$\sigma = F/(w-a)b$

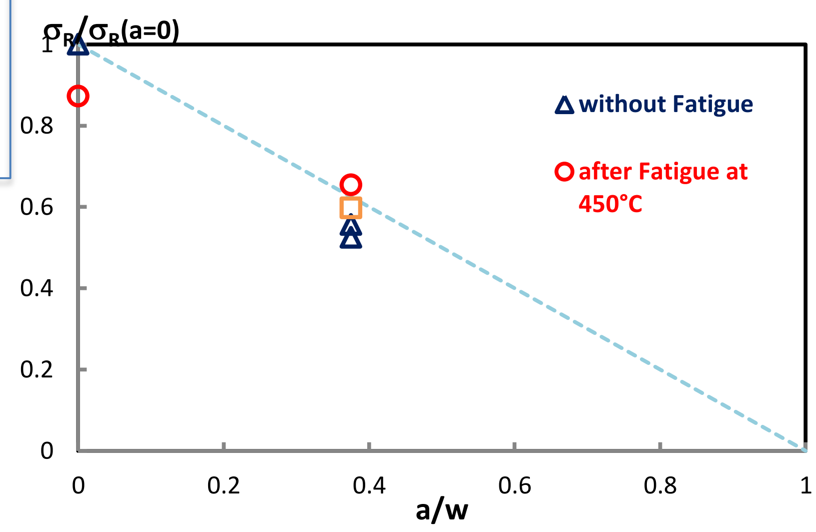




Notch insensitivity: $s_R = s_R$ (a=0).(1-a/w)

a= diameter of equivalent hole

Residual strength after static fatigue



Resistance to crack propagation

2D SiC/SiC composites

Fracture toughness:
Material property which characterizes
the initiation of fracture from a sharp crack
(obtained by fatigue cracking under plane
Strain conditions)

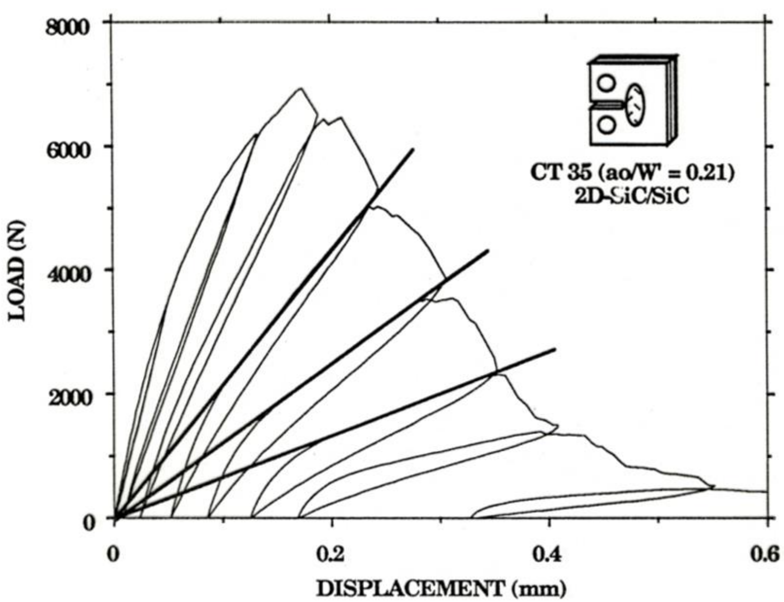
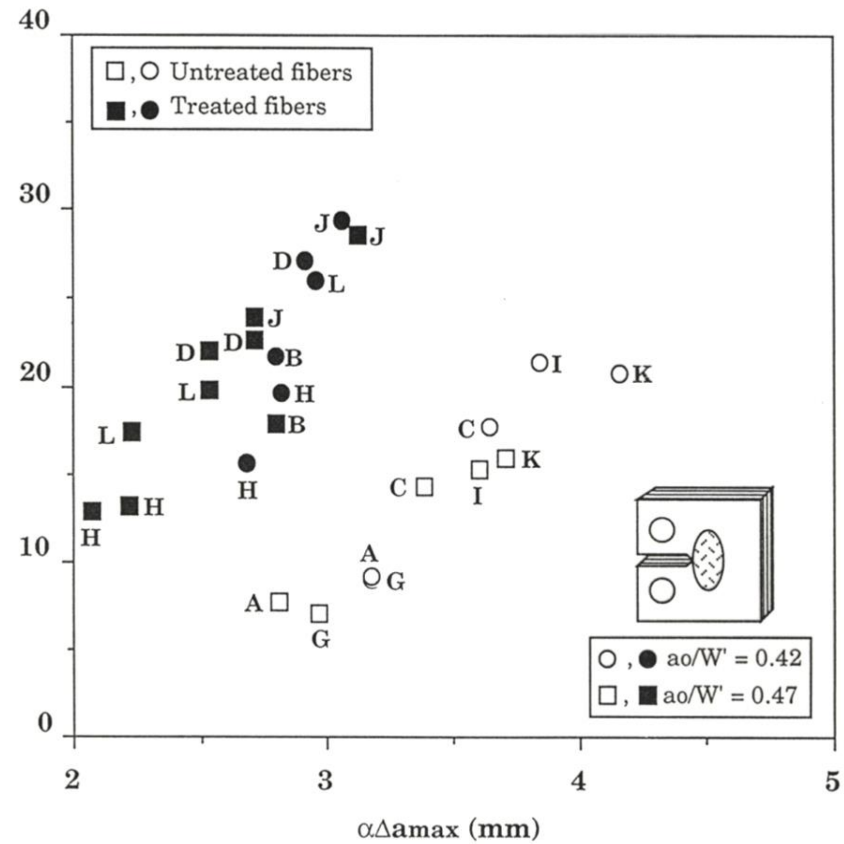


Fig. 7 : Loading-unloading curve for a CT specimen (CT 35, ao/W' = 0.21).

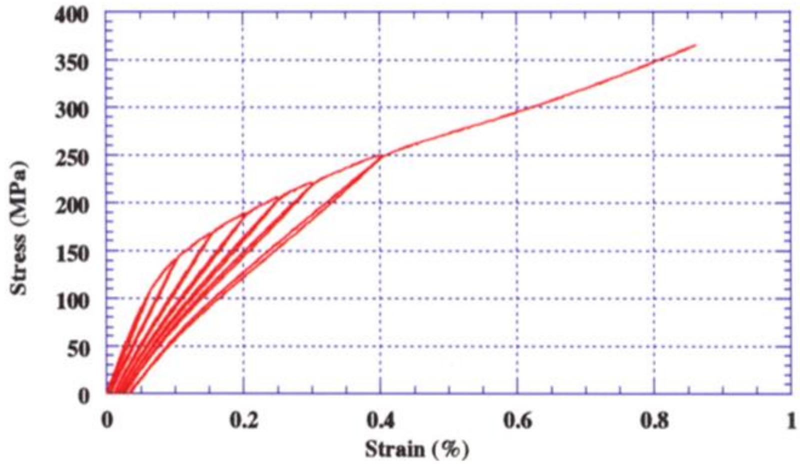


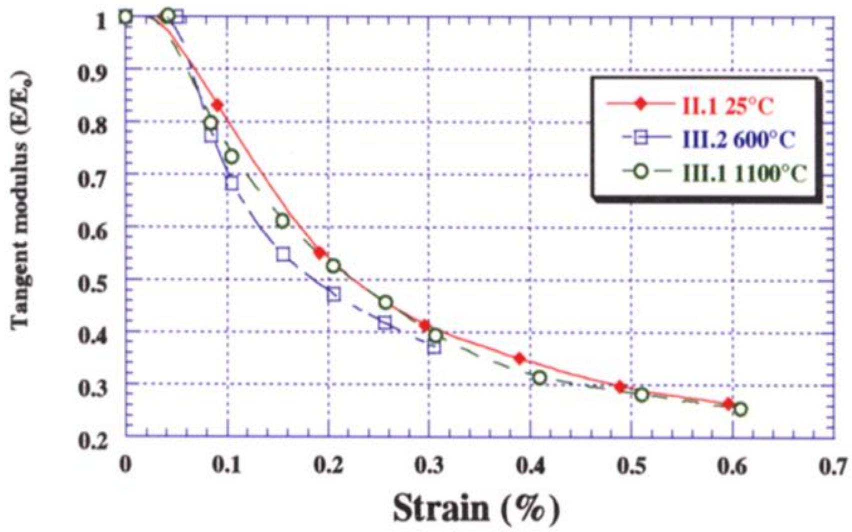
(Droillard, Lamon, 1996)

High Temperature behavior:

- monotonous loading rate
- static fatigue

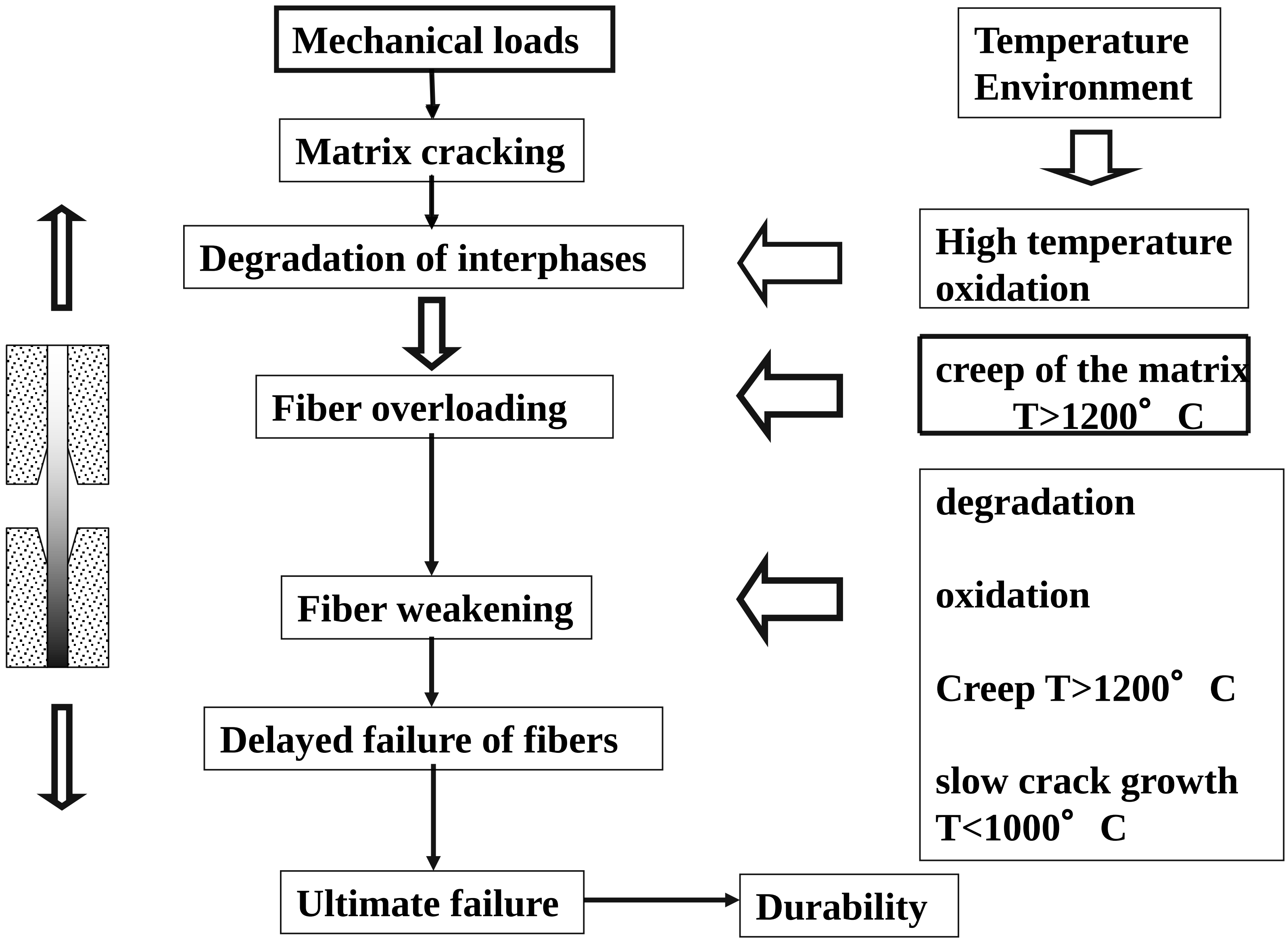
Tensile behavior at high temperature



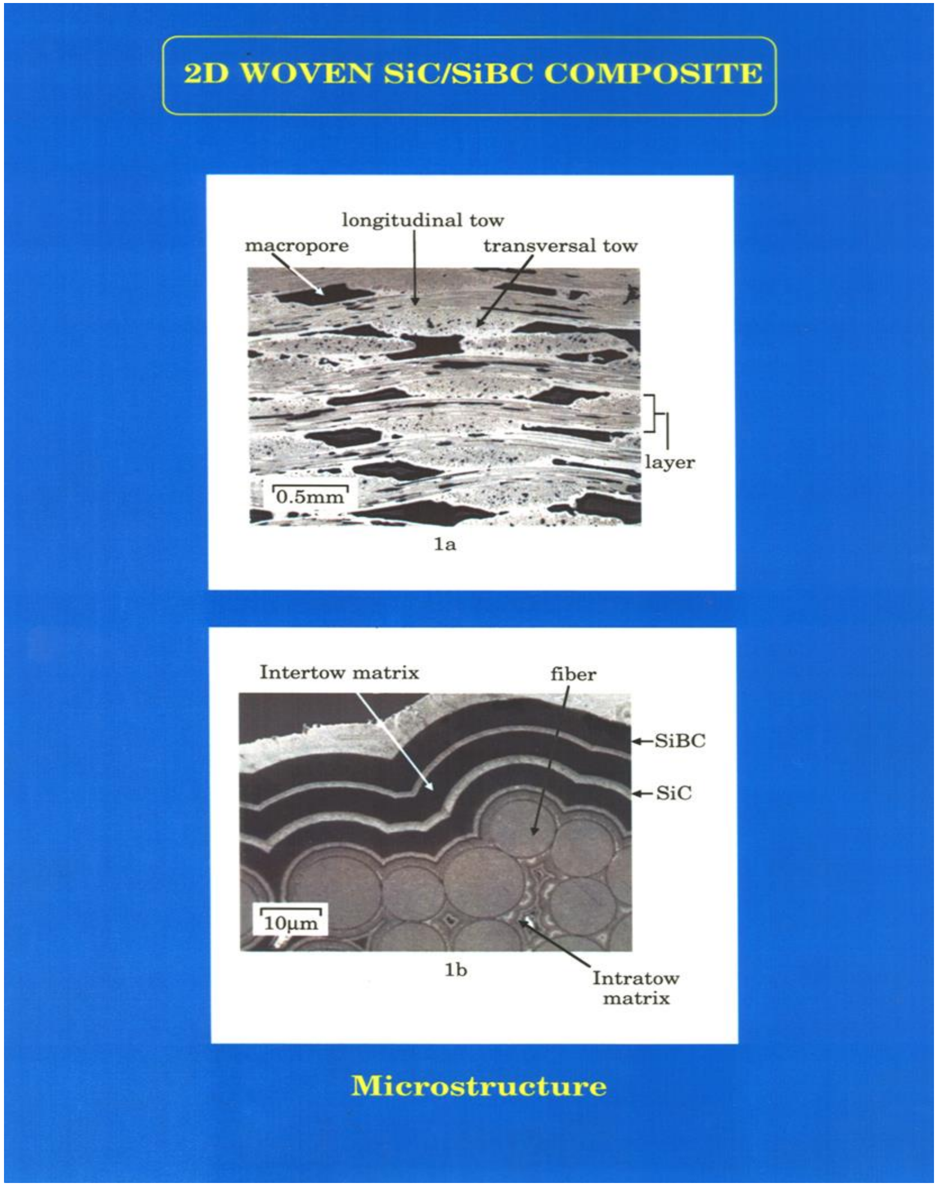


(Forio, Lamon, 2001)

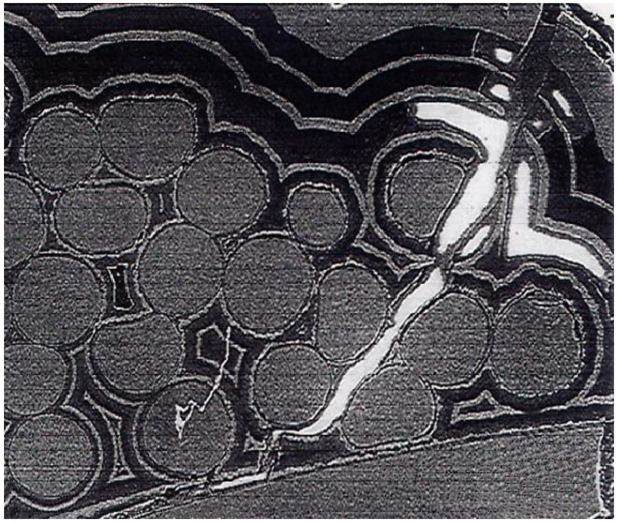
Delayed failure and lifetime at high temperature



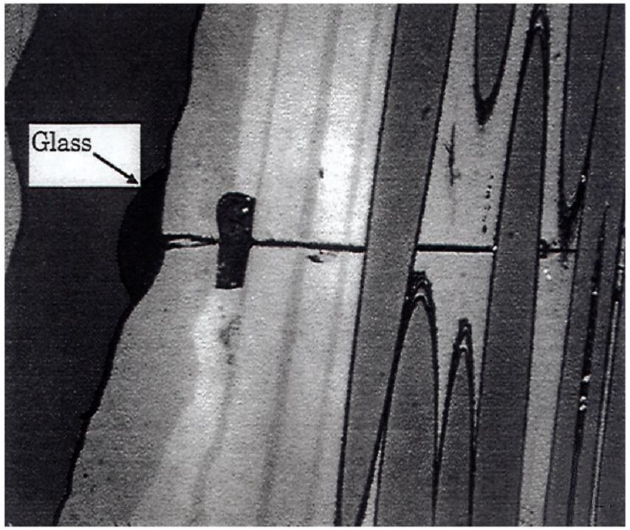
Crack healing in 2D woven SiC/SiBC composite



(Carrere, Lamon, 1999)

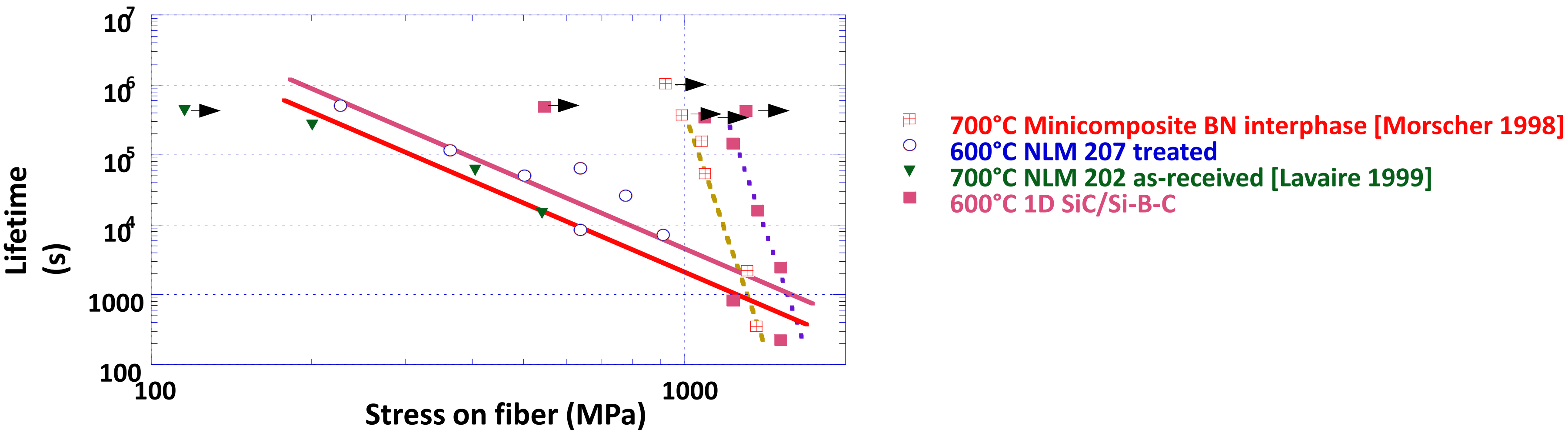


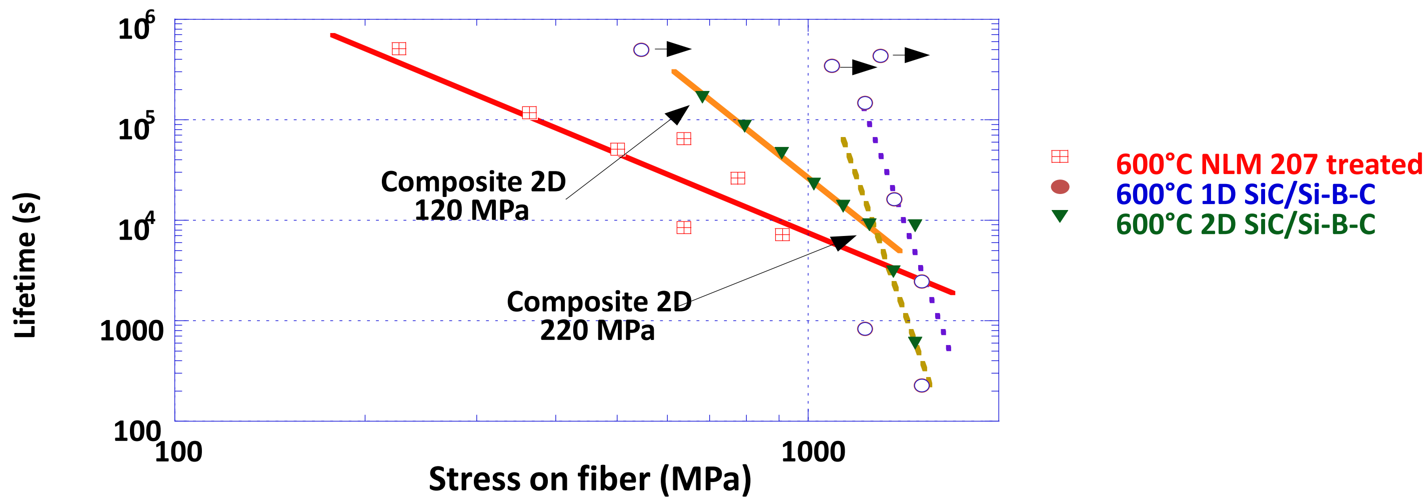
Cyclic fatigue (20 Hz) at 1200° C



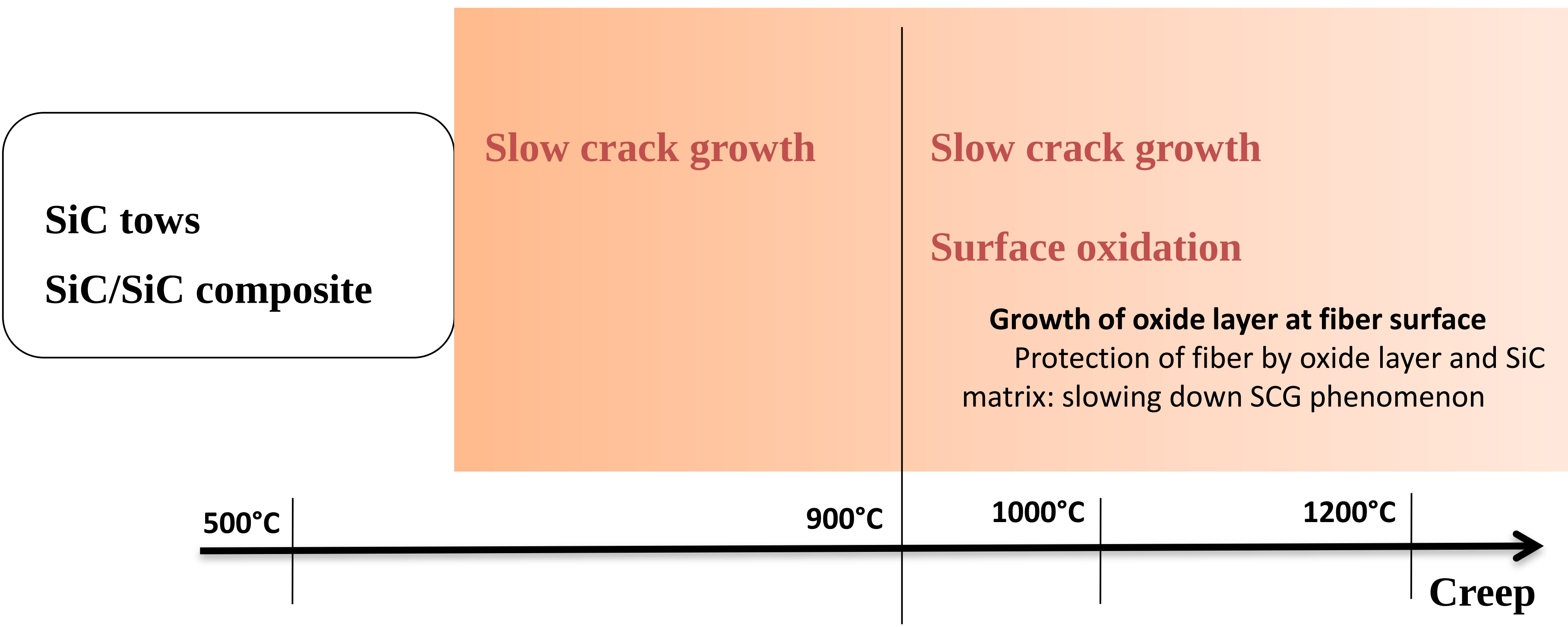
Static fatigue at 1200° C (load150 MPa)

Lifetimes in fatigue at high temperature



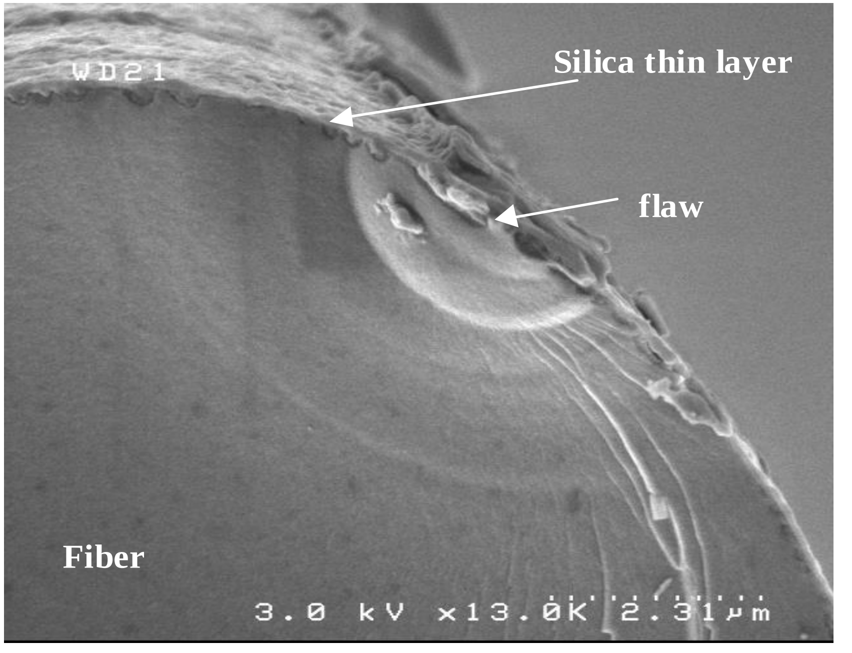


Static fatigue: slow crack growth in SiC fibers



Static fatigue: slow crack growth in SiC Nicalon tows

Fracture surface of a fiber after static fatigue on Nicalon tows at 700°C



(Forio, Lamon. JACS, 2004)

Stress intensity factors estimated from crack sizes

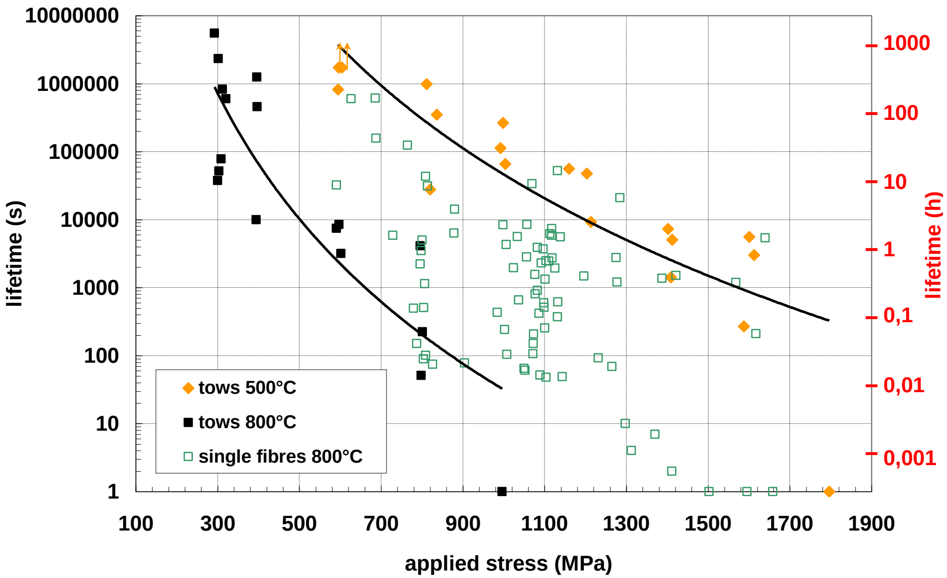
Penny shaped cracks :

$$K_I = 2\sigma\sqrt{\frac{a}{\pi}}$$

$$K_{IC} = 2MPa\sqrt{m}$$

crack length	K_I	K_I/K_{IC}
0.62	0.47	0.23
1.23	0.66	0.33
1.85	0.81	0.40
3.08	1.04	0.52

Static fatigue of SiC filaments and tows



$t\,\sigma^n = A \implies t\,\sigma^n = A_0 \exp(Ea/RT)$

Hi-Nicalon tows at 500°C and 800°C

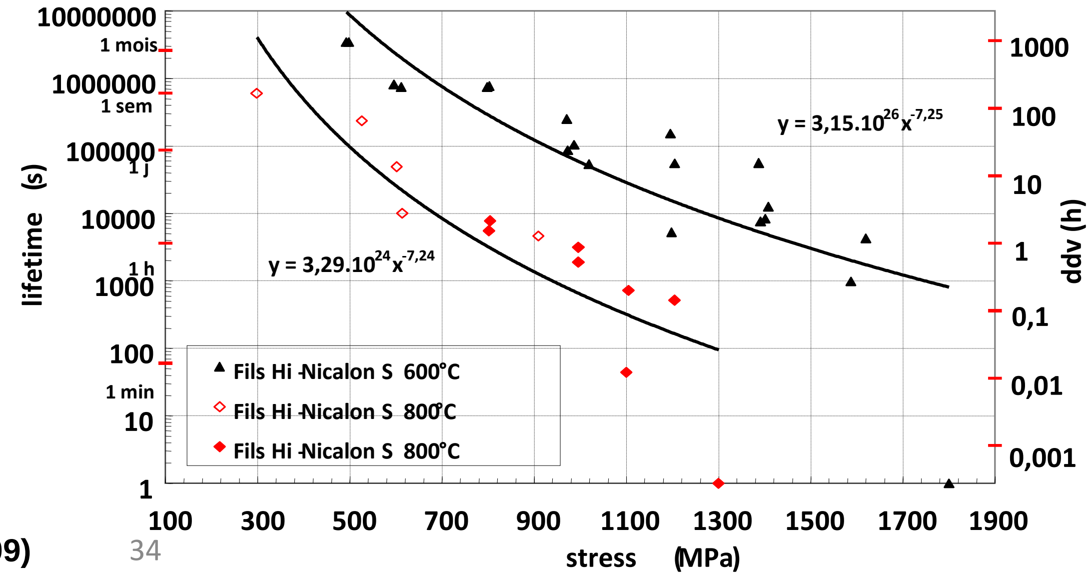
n ≈ 8.4

$A_0 = 5{,}62.10^{17}$ Ea = 182 kJ.mol^{-1}

Hi-Nicalon S tows at 600°C and 800°C

n ≈ 7,2

$A_0 = 7{,}38.10^{15}$ Ea = 178 kJ.mol^{-1}



(Gauthier, Lamon, J. Am. Ceram. Soc. 2009)

Theory: fiber lifetime distribution

- Subcritical crack growth $$V = \frac{da}{dt} = V^* \left(\frac{K_I}{K_{IC}} \right)^n$$

- Stress-strength-rupture time relation $$t = \frac{2K_{IC}^2}{V^* Y^2 \sigma^2 (n-2)} \left[\left(\frac{\sigma_f}{\sigma} \right)^{n-2} - 1 \right]$$

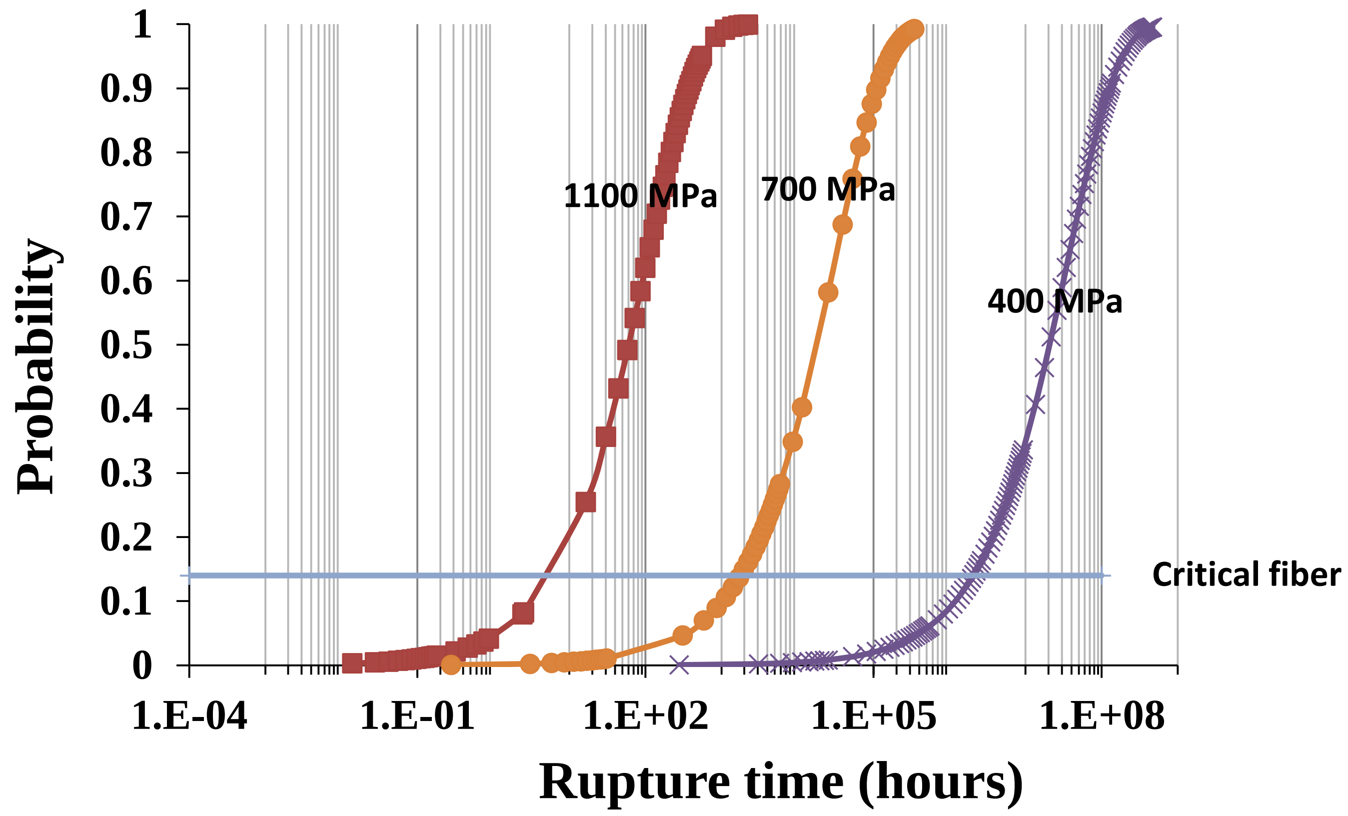
$$\sigma_{fj} = \sigma_0 \left(-\frac{v_0}{v} Ln(1 - P_j) \right)^{\frac{1}{m}}$$

- Lifetime distribution $$P(t,\sigma,v) = 1 - \exp\left[-\left(\frac{v}{v_o} \right) \left(\frac{\sigma}{\sigma_0} \right)^m \left(1 + \frac{t}{t^*} \frac{n-2}{2} \right)^{\frac{m}{n-2}} \right]$$

$$t^* = \frac{K_{IC}^2}{V^* \sigma^2 Y^2}$$

(R’Mili, Lamon, 2011, 2012)

Distribution of lifetimes under constant stresses



Hi Nicalon S filaments @800°C in air

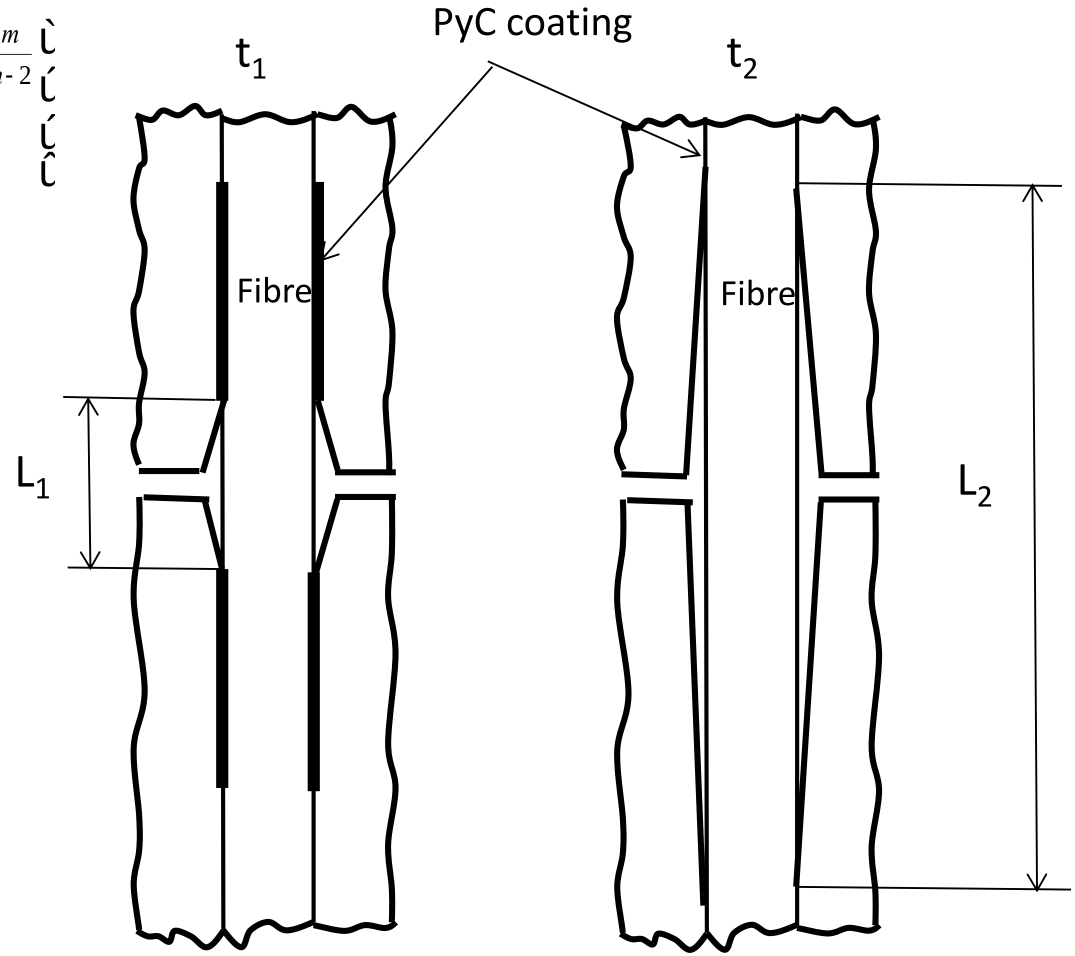
(R'Mili, Lamon, 2015)

Size dependence of rupture time

$$P(t,\sigma,v) = 1 - \exp\left[-\left(\frac{v}{v_o}\right)\left(\frac{\sigma}{\sigma_0}\right)^m \left(1 + \frac{t}{t^*}\frac{n-2}{2}\right)^{\frac{m}{n-2}}\right]$$

$$\frac{t_2}{t_1} = \left(\frac{L_1}{L_2}\right)^{\frac{n-2}{m}}$$

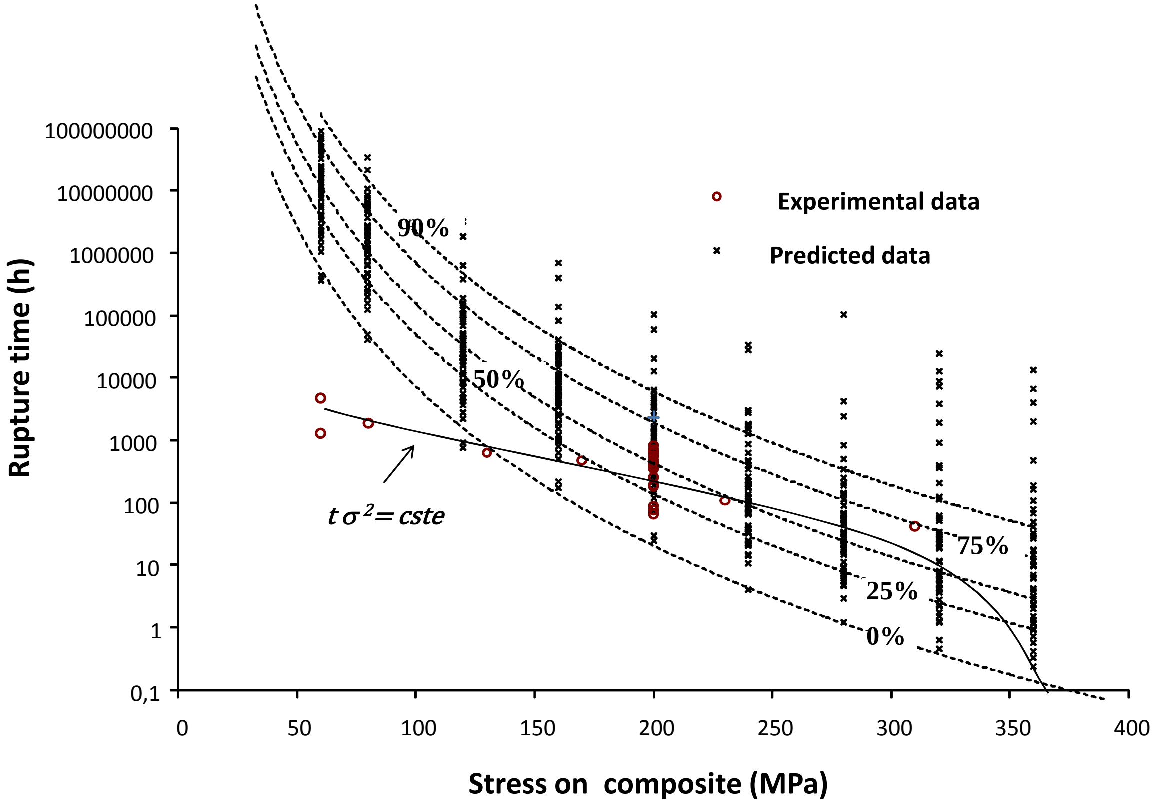
L (mm)	t (hours)
1	629861
10	17395
20	5904
25	4170
50	1415
60	1065
75	752
100	480
150	255



Influence of oxidation of PyC interphase in SiC/SiC: size effects
On lifetime of SiC filament (P=0.1) at 500°C under 700MPa

(R'Mili, Lamon, 2011, 2012)

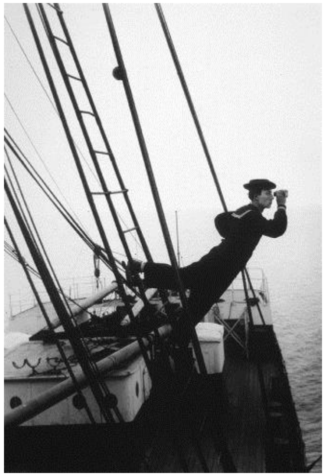
Stress-Probability-Time diagrams for 2D SiC/SiC



Static fatigue at 500°C

(Loseille, Lamon, 2010)

Conclusions



- CMCs are versatile and smart materials
- Significance of microstructure/properties relationships
- Theoretically, composites can be designed with respect to end use applications
- Empirism still prevails
- But, composite design can be based on models
- Multiscale bottom up models are required: damage processes, failure mechanisms at pertinent scales, constituents properties, interface mechanics, and scale to scale changes
- Interface engineering, processing, treatment and new fibres and matrices (?)

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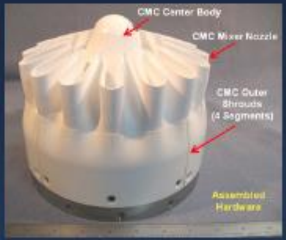

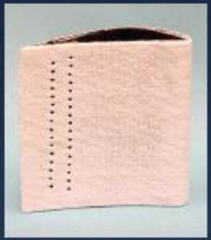

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