Subcritical crack growth in ceramic materials

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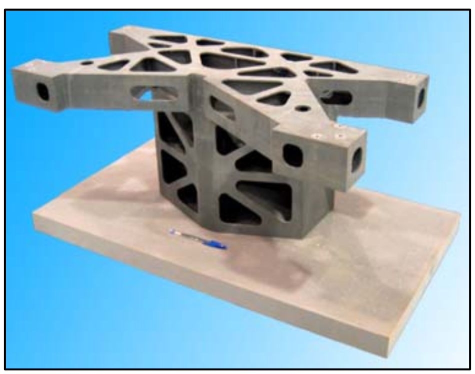
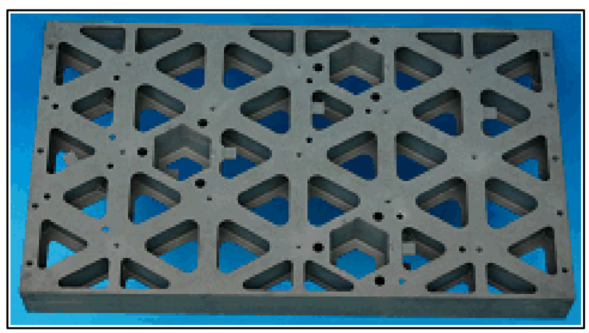
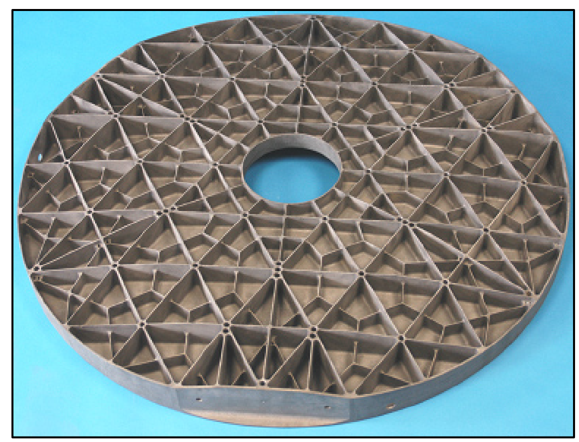
Introduction

- **Context**
  - Ceramic materials increasingly used for structures and optical instruments in space applications
  - Trend to build larger and load carrying ceramic structures
  - Brittle behavior of ceramic materials imposes dedicated design and verification approaches



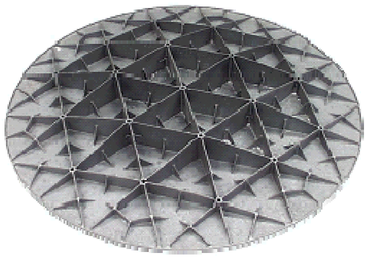




Introduction (cont'd)

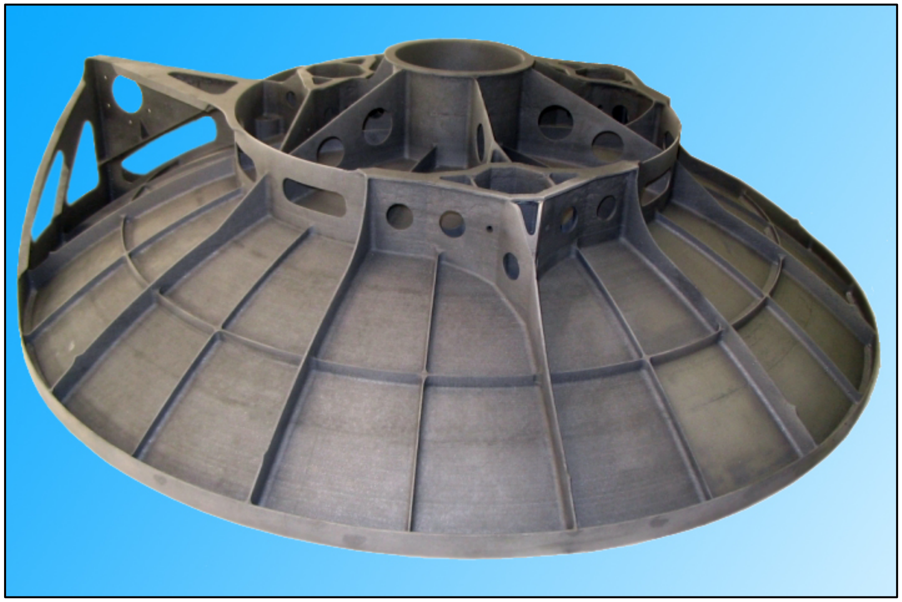
- **The problem**
  - Brittle materials usually contain small flaws or other geometric features which determines their strength
  - Specific to subcritical crack growth: propagation of cracks under static loading

- **The materials, used in structural space applications:**
  - Zerodur (Schott, Germany)
  - Silicon carbide (SiC100, Boostec, France)
  - Carbon reinforced silicon carbide (Cesic ® and HB Cesic®, ECM, Germany)



Theoretical background

- Fracture mechanics of brittle materials
- Weibull statistical distribution
- Subcritical crack growth

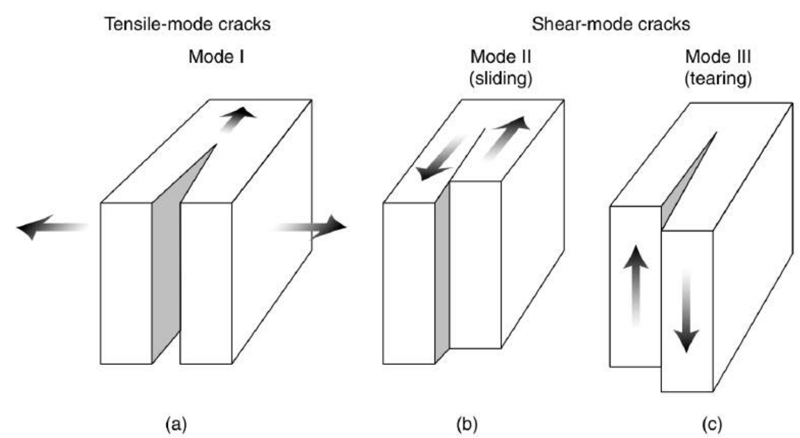


Fracture mechanics of brittle materials

- **Fracture mechanics:** used to analyze cracks in engineering components

- **Theory of fracture mechanics:**
  - Theory that treats a crack in a continuous body while avoiding the detail of what happens on an atomic scale.

- **Three loading modes:**
  - Mode I: tension normal to crack plane
  - Mode II: shear loading in crack direction
  - Mode III: "out of plane" shear loading



Fracture mechanics of brittle materials (cont'd)

- **Introduction of K, stress intensity factor:**
  - $K<K_c$ no crack propagation
  - $K>K_c$ the material fails: $$\sigma_f = \frac{YK_{IC}}{\sqrt{a}}$$
    - σ_f: failure strength
    - K_{IC}: critical stress intensity in mode I
    - Y: crack and geometry factor
    - a: crack size

Weibull Statistical Distribution

- **Two parameter Weibull model :**

$$F(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0} \right)^m \right]$$

- **Three parameter Weibull model:**

$$F(\sigma) = 1 - \exp\left[-\left(\frac{\sigma - \theta}{\sigma_0} \right)^m \right]$$

-F(σ) : probability of failure at any stress σ,

-m: Weibull modulus, describes the homogeneity of the flaw distribution

-σ_0: scale parameter or characteristic strength (F(σ_0)=63.21%)

- θ threshold parameter

Two parameter Weibull Distribution

- **Based on two assumptions:**
  - The weakest link argument (failure at any flaw leads to total failure)
  - A distribution function

- **The allowable stress** is not a fixed value but depends on the volume or the surface under stress:
  - High m: small volume effect
  - Small m: strong volume effect

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_2}{V_1}\right)^{\frac{1}{m}}$$

- **Parameters determined by test:**
  - Confidence on parameter values depends on the number of samples

How to define the Weibull parameters by test?

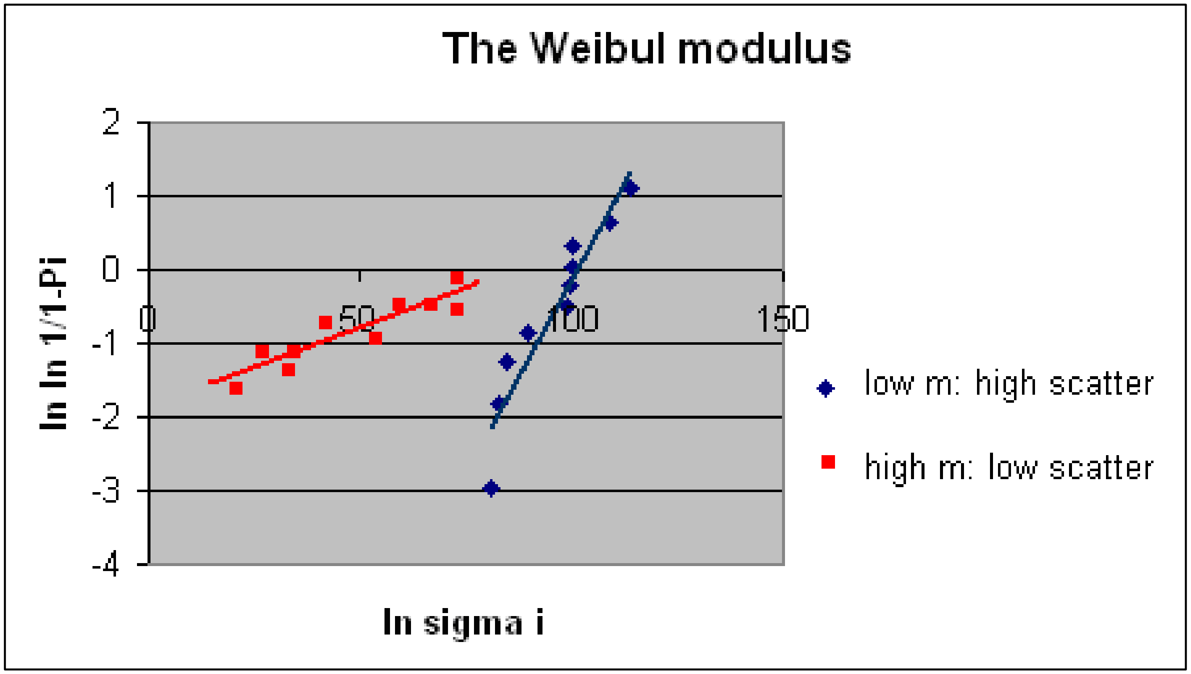
- $F(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0} \right)^m \right]$ ➔ y=ax+b
- By taking its' logarithmic form: $\ln(\ln(\frac{1}{1-F})) = m \ln \sigma - m \ln \sigma_0$
- Cumulative failure probability (relative to a batch of experiments): $F_{fi} = \frac{i-0.5}{n}$
- Corresponding failure stresses σ_{fi} in ascending order: $\sigma_{f1} \leq .. \leq \sigma_{fi} \leq .. \leq \sigma_{fn}$

How to define the Weibull parameters by test?

- Plot the failure probabilities as a function of the failure strengths:

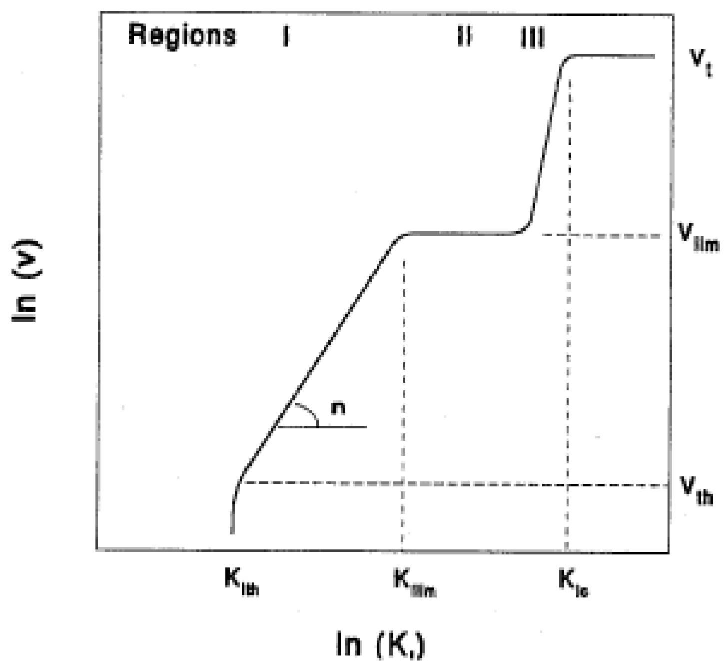
- m: slope of the fitted straight line

- σ_0: obtained at $\ln(\ln(1/1-Pi))=0$



Subcritical Crack Growth

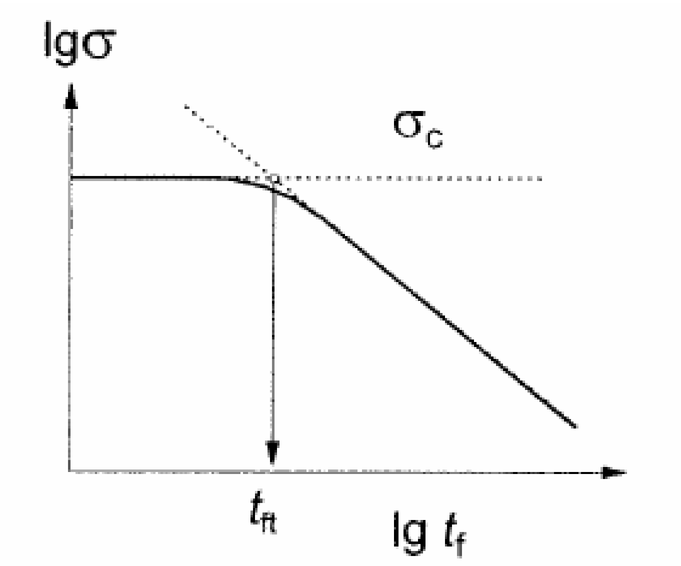
- **Time dependant phenomenon**
  - A crack grows at constant load
  - Can be described in a v-K diagram
  - Three regions can be observed
  - In region I: $v = \dfrac{da}{dt} = A\left(\dfrac{K_I}{K_{IC}}\right)^n$
    - v: crack velocity
    - a: crack size
    - A, n: crack growth parameters



➔ If the v-K curve is known, lifetime predictions can be made

Subcritical Crack Growth

- **Static fatigue** (constant load, σ(t)=cst): $t_f = B\sigma_c^{n-2}\sigma^{-n}\left[1-\left(\frac{\sigma}{\sigma_c}\right)^{n-2}\right]$



Two asymptotes: • $\sigma = \sigma_c$

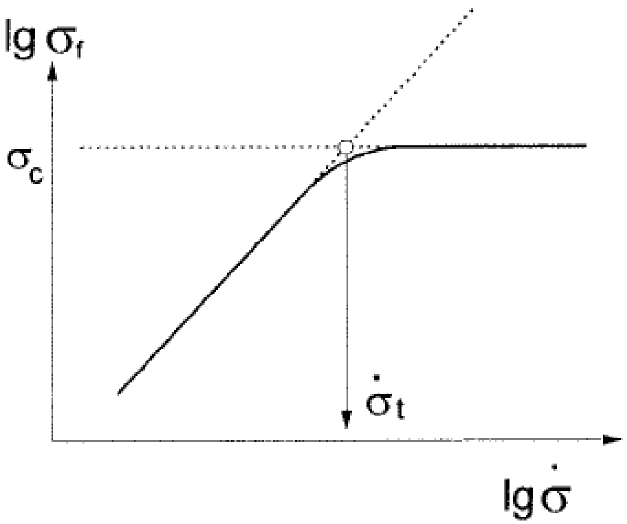
• $t_f = B\sigma_c^{n-2}\sigma^{-n}$

Intersection: $t_{ft} = \frac{B}{\sigma_c^2}$

With: $B = \frac{2}{n-2}\frac{1}{AY^2K_{IC}^{n-2}}$

Subcritical Crack Growth

- **In dynamic fatigue** (constant load rate): $\sigma_f^{n+1} = B(n+1)\sigma_c^{n-2}\dot{\sigma}\left[1-\left(\frac{\sigma_f}{\sigma_c}\right)^{n-2}\right]$



Two asymptotes:

- $\sigma_f = \sigma_c$
- $\sigma_f^{n+1} = B\sigma_c^{n-2}\dot{\sigma}(n+1)$

Intersection: $\dot{\sigma}_t = \frac{\sigma_c^3}{B(n+1)}$

With: $B = \frac{2}{n-2}\frac{1}{AY^2 K_{IC}^{n-2}}$

Subcritical Crack Growth

- **Determination of A and n parameters by test and lifetime calculations:**
  - using the equation of the second asymptote in dynamic fatigue:

$$\sigma_f^{n+1} = B\sigma_c^{n-2}\,\dot{\sigma}(n+1)$$

  - **n and A** are evaluated by application of its' logarithmic form:

$$\ln(\sigma_f) = \frac{1}{n+1}\ln\dot{\sigma} + \frac{1}{n+1}\ln\left[(n+1)B\sigma_c^{n-2}\right]$$

  - n is the slope of the ln(σ)-ln(dσ/dt) plot
  - the quantity $B\sigma_C^{(n-2)}$ is obtained from the location of the straight line

Crack propagation in Zerodur

- Analysis of dynamic fatigue tests done by Astrium and NASA

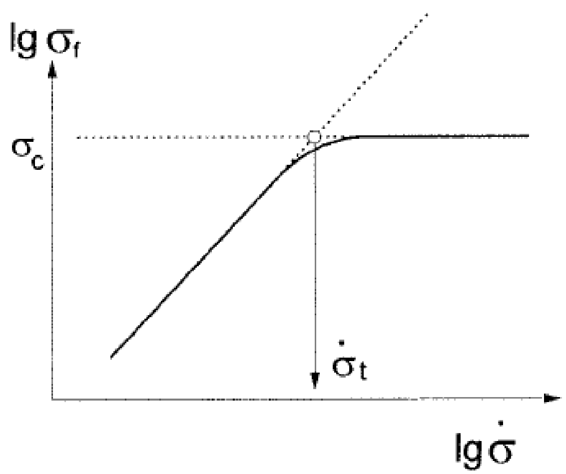
	Astrium		NASA (notched specimens)		
Environment	50% RH		Water	Water	50% RH
Number of samples tested	138	58	Unknown		
Load rate (MPa/s)	2	0.2	0.06/1.8/11/ 121.5	0.05/1/4.5/ 121.5	0.014/0.13/ 0.36/1.3
n	41.4		23.6	23.5	45.2
ln(B)	Not calculated		-2.192	-3.631	-13.885
K_{IC} (MPa.m$^{1/2}$)	0.9		0.9		

•NASA-TM-4185-Fracture toughness and crack growth of Zerodur

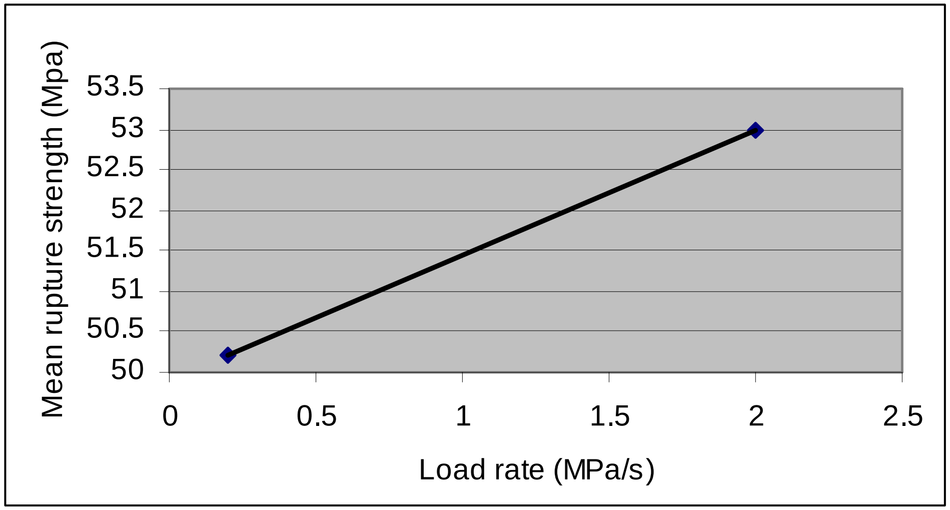
•Strength_ZerodurD151_SPIE optics And Photonics Conference 2007

Crack propagation in Zerodur

- Evolution of the mean failure strength as a function of the load rate:



- Zerodur, 2 load rates:

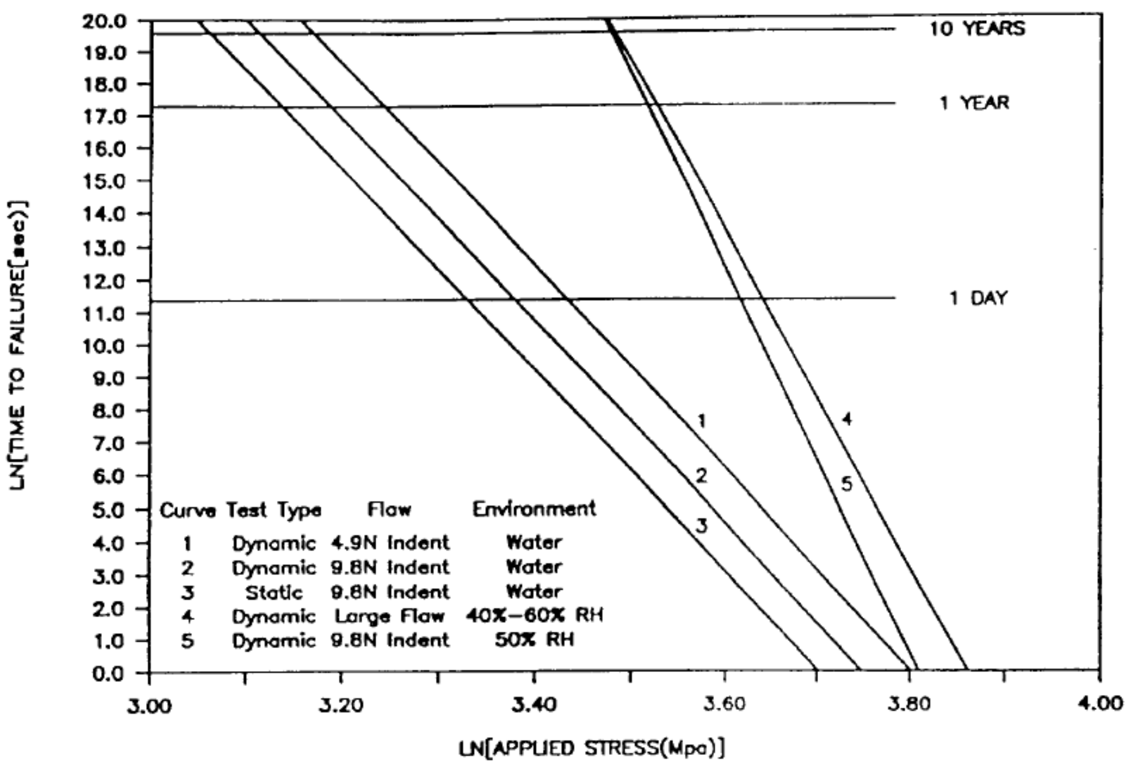


➔ Two load rates is insufficient to make conclusions

Crack propagation in Zerodur

- Lifetime of Zerodur as a function of stress level
  - Curve 4 (highest slope)

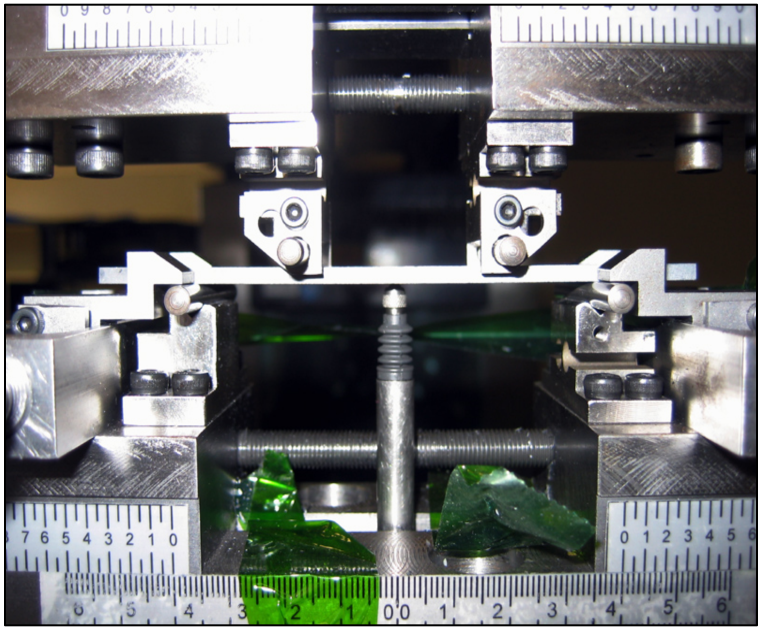
Applied load (MPa)	Time to failure
50	0s
40	1 day
37	1 year
35	10 years



⇨ the higher n, the less sensitive to subcritical crack growth a material is.

Fatigue tests on HB Cesic®

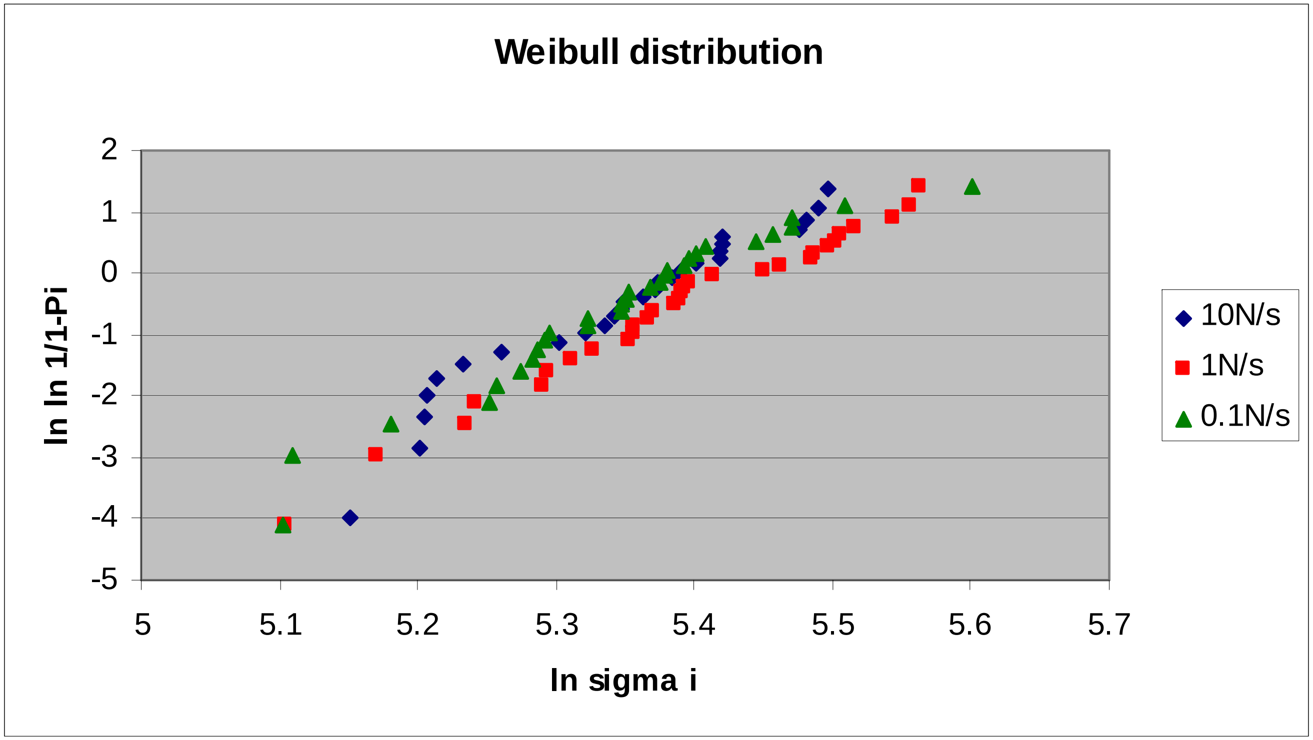
- Analysis of tests by Thales Alenia Space on HB Cesic®
  - 4 point bending
  - 90 rectangular samples, unnotched
  - 3 load rates (10N/s, 1N/s and 0.1N/s)
  - loaded at constant load rate until failure



➔ Evaluate possible subcritical crack growth and related parameters

Fatigue tests on HB Cesic®

- Weibull analysis for the three load rates:



Fatigue tests on HB Cesic®

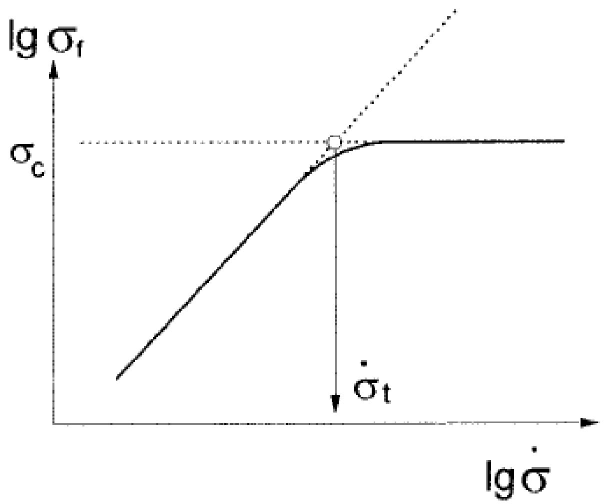
– Weibull modulus (m) in the same range ($m_{0.1N/s}$ =9, $m_{1N/s}$ =10, $m_{10N/s}$ =12)
– Weibull strength (σ_0) close for 0.1N/s and 1N/s but slightly lower for 10N/s

➔ Very little effect of load rate, and not in the way corresponding to subcritical crack growth

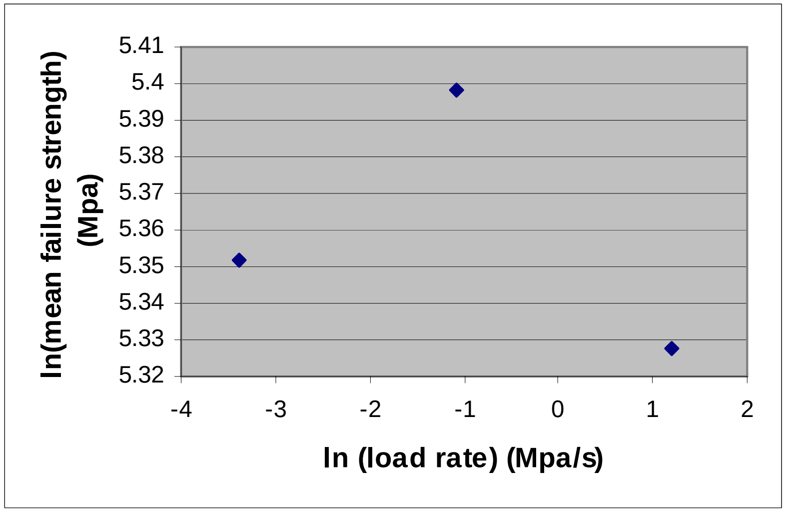
– Investigation in ESTEC labs by binocular and SEM to inspect the fracture surfaces, to assess the validity of the results and look for crack initiation location

Fatigue tests on HB Cesic®

- Evolution of the mean failure strength as a function of the load rate:



- Three load rates:



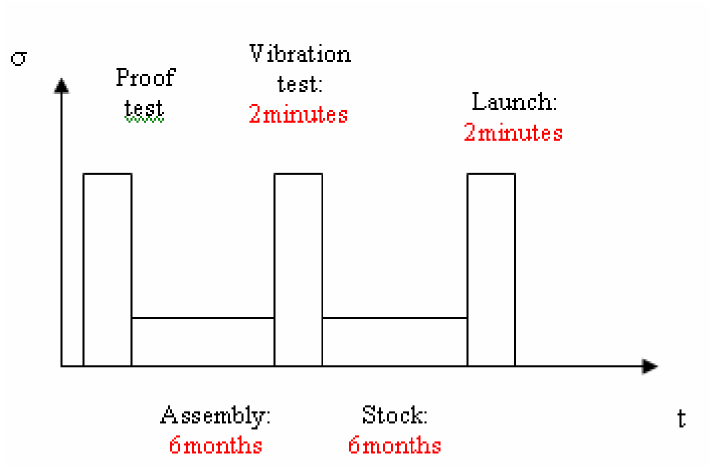
➔ No trend can be found, HB Cesic® probably insensitive to subcritical crack growth. To be confirmed by further tests with 4 load rates

Perspectives

- Establish if the considered materials are sensitive to subcritical crack growth

- Implement in Nasgro/ESACrack the test results

- Define materials lifetime
  by taking into account the life cycle



- Coming TRP study on methodology for design and verification for ceramic structures

Conclusions

- Need to assess the criticality of subcritical crack growth for ceramics
- Need to characterize the materials
- From tests ➔ HB Cesic® insensitive to subcritical crack growth
- Use these parameters to asses integrity over life cycle

Thank you for your attention!

Questions?