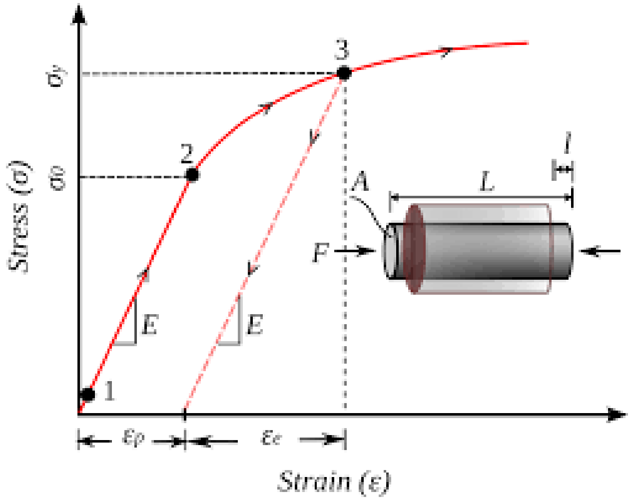
Centro Italiano Ricerche Aerospaziali

WORKSHOP
Università di Salerno 24-5-2019
Aircraft turbine design

Thermomechanical design of rocket engine thrust chambers

M. Ferraiuolo



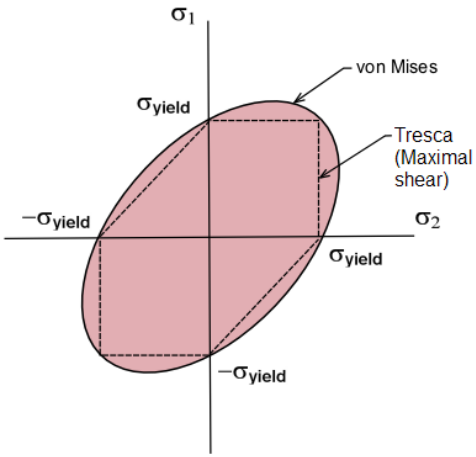


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TABLE OF CONTENTS

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TABLE OF CONTENTS

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INTRODUCTION

- This work has been conducted in the frame of the Hyprob-new project

- The aim of the Hyprob-new Project, funded by MIUR, is to enable and improve National system and technology capabilities on liquid rocket engines (LRE), Propulsion systems for future space applications with specific regard to LOX/LCH4 technology

In particular, the aim is to develop:

- technology demonstrators, including intermediate breadboards;

- R&D activities in relevant technology areas;

- Improvement of test capabilities.

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INTRODUCTION

REGENERATIVE COOLING

- **the fuel acts as a coolant and is passed through the coolant channels in the periphery of the chamber wall**
- **It is the most efficient method of cooling since the heat absorbed by the coolant/fuel increases the enthalpy in the cooling channels leading to a more efficient combustion,**
- **The adoption of regeneratively cooled thrust chambers for aerospace applications is necessary when high heat fluxes coming from the combustion chamber are detected**

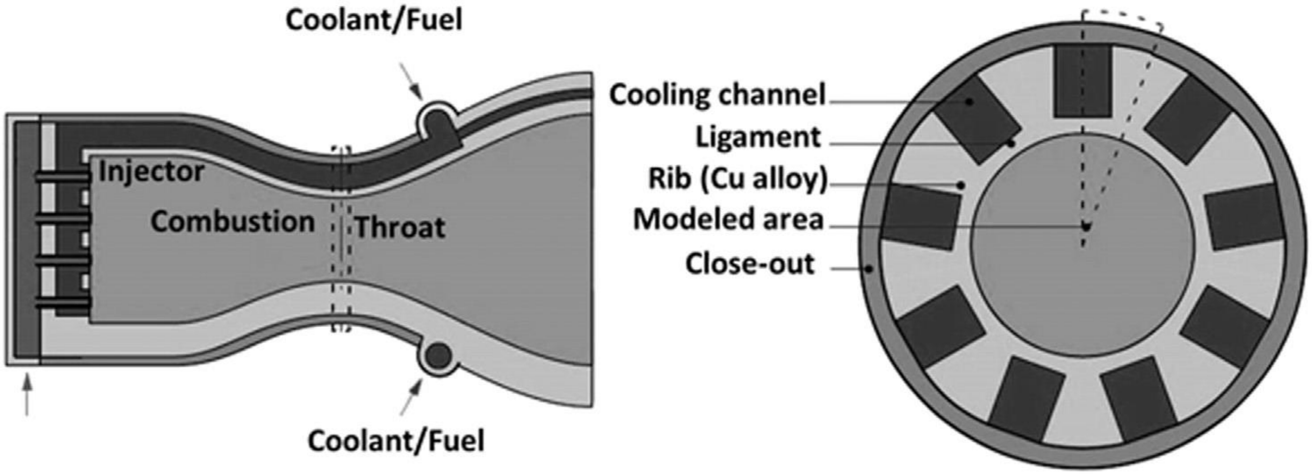

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TABLE OF CONTENTS

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MATHEMATICAL MODEL - PLASTICITY

The transient heat conduction problem inside a solid body is governed by the differential equation:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=\frac{\rho c}{k}\frac{\partial T}{\partial \theta}$$

temperature and heat flux continuity conditions are applied at the interface between generic materials *a* and *b*:

$$k_a\frac{\partial T_a}{\partial n}=k_b\frac{\partial T_b}{\partial n} \qquad\qquad T_a=T_b$$

Convective boundary conditions:

$$-k\frac{\partial T}{\partial n}=h(T-T_\infty)$$

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Mathematical Model - plasticity

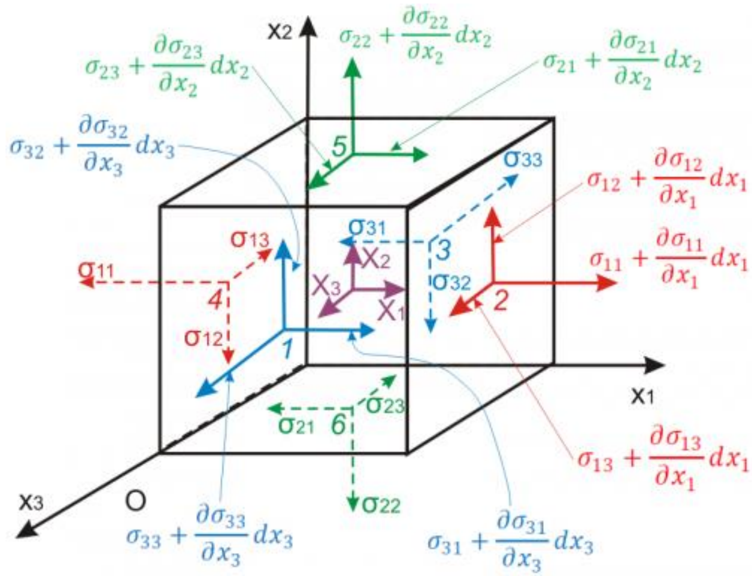
The equilibrium equation for an elastic body is expressed as follows:

$$\sigma_{ij,i} + X_i = 0$$

Where:

- **σ_{ij} is the Cauchy stress tensor,**
- **X_i represents the body force per unit volume.**

The elastic equilibrium equation must be combined with the compatibility equations and with the constitutive laws where the strain tensor is a linear function of the stress tensor and of the strain tensor related to the temperature changes with respect to the reference temperature (temperature at which no thermal strain are detected)



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MATHEMATICAL MODEL - PLASTICITY

In general plasticity models are identified by:

- <u>Yield criterion</u> delimits the elastic stress states (lying within the yield surface), and the plastic stress states (lying on or outside the yield surface)

- <u>Hardening/Softening</u>

- <u>Flow rule</u> identifies the relationship between the plastic strain increment and the deviatoric stresses

The total strain ε is decomposed into elastic and plastic components:

$$\boldsymbol{\varepsilon_{ij} = \varepsilon_{ij}^{el} + \varepsilon_{ij}^{pl}}$$

The viscoplastic model identified adopts the Von Mises yield criterion, the bilinear kinematic hardening rule, the Prandtl-Reuss flow rule and, finally, the Norton's law to describe the creep phenomenon

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MATHEMATICAL MODEL - PLASTICITY

- **Yield criterion**

$$F(\boldsymbol{\sigma}, k, \boldsymbol{\alpha}) = 0$$

k represents the plastic work, and α the translation of the yield surface (back stress tensor)

$$k = \int \boldsymbol{\sigma}^T [M] \boldsymbol{d\varepsilon^{pl}}$$

- **Flow rule**

$$d\boldsymbol{\varepsilon}_{ij} = \boldsymbol{S}_{ij} d\lambda$$

$\boldsymbol{d\varepsilon_{ij}}$ **are the plastic strain increments,** $\boldsymbol{S_{ij}}$ **are the deviatoric stresses and** $\boldsymbol{\lambda}$ **is the plastic multiplier which is evaluated by imposing that the stress state lies on the yield surface during plastic flow**

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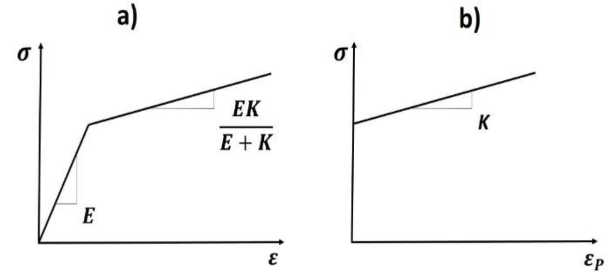
MATHEMATICAL MODEL - PLASTICITY

- **Hardening**

$$\sigma = \begin{cases} E\varepsilon \; if \; \gamma = 0 \\ \dfrac{EK}{E+K}\varepsilon \; if \; \gamma > 0 \end{cases}$$



where γ is the absolute value of the plastic strain rate and K is the plastic modulus

- **Creep**

the Norton's law, adopted for primary and secondary creep regimes, defines how the creep strain rate is affected by the stresses

$$\dot{\boldsymbol{\varepsilon}} = B\boldsymbol{\sigma}^n$$

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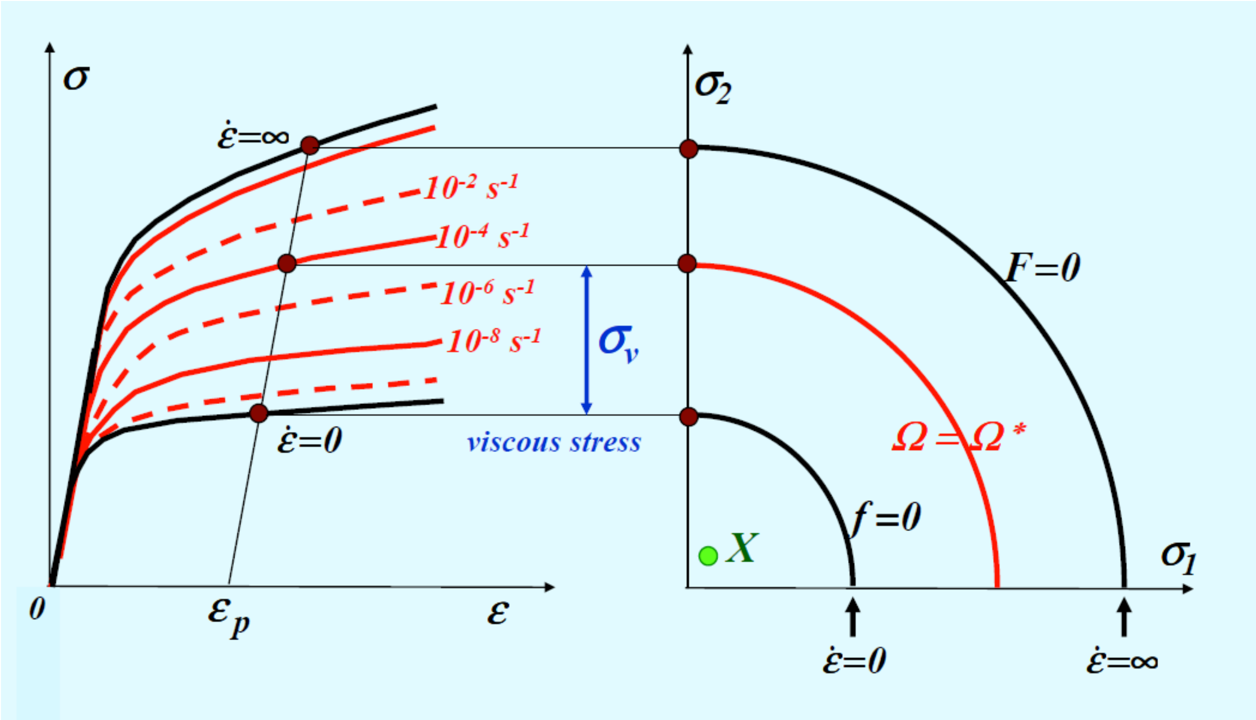
MATHEMATICAL MODEL - PLASTICITY

Rate dependent plasticity: A change in the rate of strain during the test results in an immediate change in the stress–strain curve.

Perzyna and Pierce models take into account the effects of rate dependent plasticity



J.L. Chaboche, «Elasto-viscoplasticity», ATHENS – Course MP06 – 16 – 20 March 2009

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MATHEMATICAL MODEL - PLASTICITY

Robinson's Vicoplastic model

- **The model includes two internal state variables to account for the kinematic and isotropic hardenings**
- **The material behavior is linear elastic for all the stress levels within the dissipation potential and non linear viscoplastic for the stress levels outside**
- **The FE viscoplastic model implemented in Ansys does not take into account the effects of isotropic hardening**

V.K. Arya, A. Kaufman, Finite element implementation of Robinson's viscoplastic model and its application to some uniaxial and multiaxial problems, J. Eng. Comput. 6 (3) (1989) 537–547.

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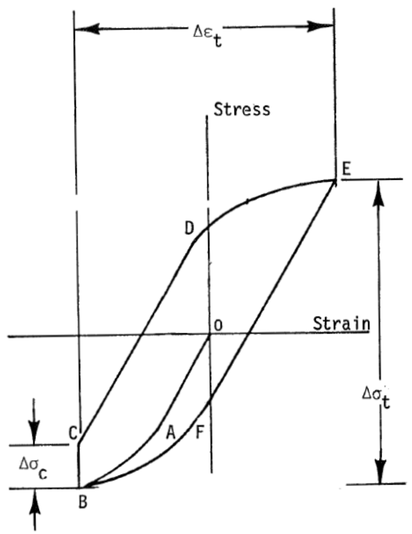
MATHEMATICAL MODEL - PLASTICITY

Porowski Vicoplastic model

- The model includes strain rate dependent effects
- Strains are evaluated considering average temperatures in the ligament and in the closeout wall
- Norton's law is considered to take into account creep effects



J.S. Porowski, W.J. O'Donnell, M.L. Badlani, B. Kasraie, Simplified design and life prediction of rocket thrust chambers, J. Spacecr. Rocket. 22 (2) (1985) 181–187.

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TABLE OF CONTENTS

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- ***Low cycle fatigue***

The strain range at the minimum ligament section increases with progressing distortion and thinning

- ***Thermal Ratcheting***

At the peak of the heat transient, the ligament yields in compression. The stresses are compressive during the creep period, then yields in tension at the cold end of the cycle and ductile failure due to plastic tensile instability. The ligaments are subjected to incremental permanent deformations during each firing cycle of the thrust chamber. The geometry changes as the incremental strains accumulate. They are subjected to incremental bulging and progressive thinning near the center of the ligament.

- ***Creep***

When the pressure acting on the ligament is high, the hoop stress relaxes quite rapidly becoming tensile on the hot-gas-wall surface of the ligament

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- Several studies have demonstrated that the choice of the hardening model is crucial since it influences in a significant way the type of failure predicted by the numerical analyses

- Eslami demonstrated that reversed plasticity (zero net plastic deformation) is predicted if zero mean mechanical load is applied and isotropy of tension/compression curve

- Ratcheting can be predicted adopting non linear hardening rules (Frederick Armstrong) when non zero mean loading and thermal loading is considered

H. Mahbadi, M.R. Eslami, «Cyclic loading of beams based on the Prager and Frederick–Armstrong kinematic hardening models», International Journal of Mechanical Sciences 44(2002) 859-879

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TABLE OF CONTENTS

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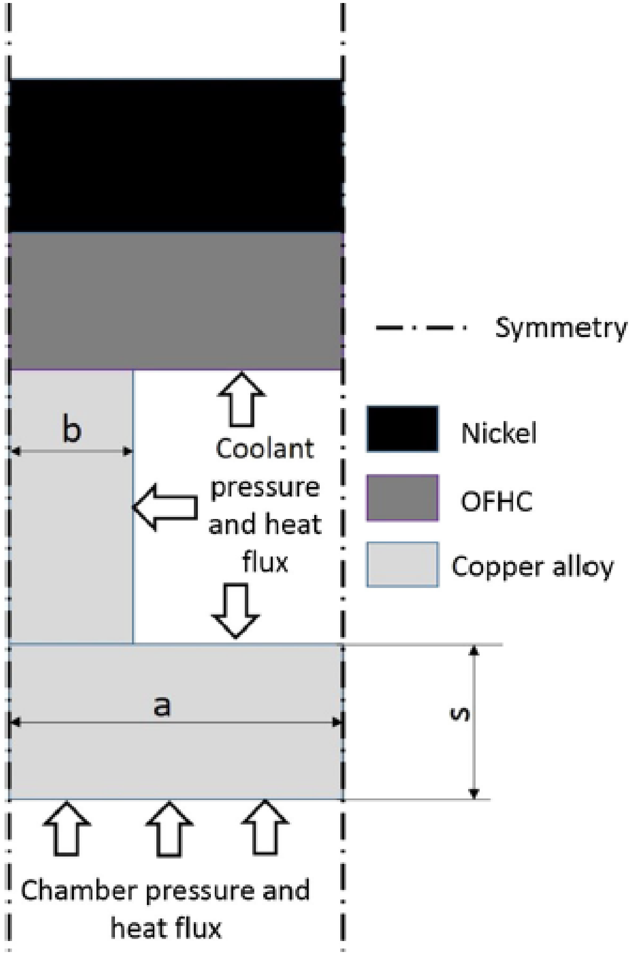
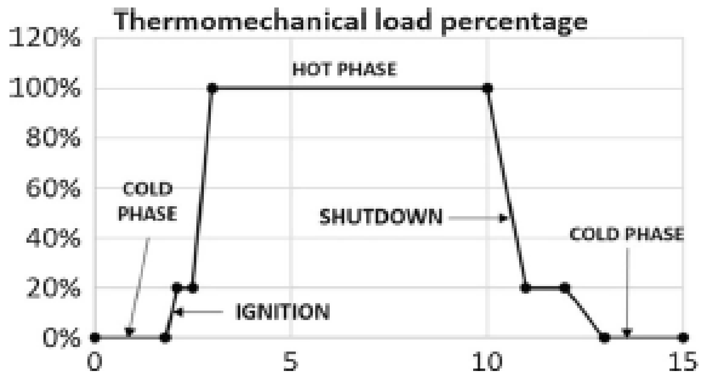


- **Half cooling channel is studied taking advantage of the symmetry conditions.**
- **The thermomechanical load cycle adopted is representative of a typical experimental hot fire test which is made of three stages: ignition, hot phase and shutdown.**



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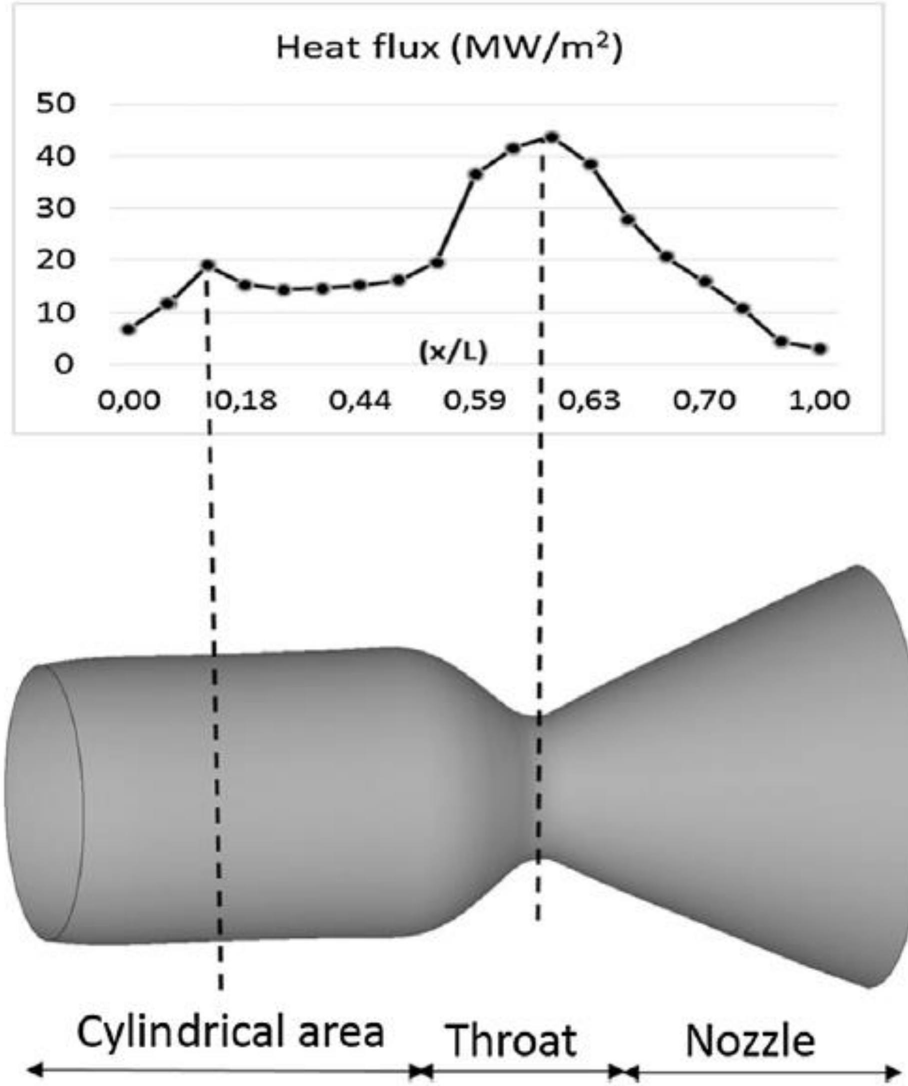
Finite Element Model

- **the maximum heat flux value occurs in the throat region and a heat flux peak can be detected in the cylindrical part of the chamber**.
- **the cooling efficiency of the chamber section channel is considerably lower since the coolant temperature is higher and the heat transfer coefficient is smaller (the section area is significantly higher than that of the throat section, and consequently, the fluid velocity and the heat transfer coefficient are smaller).**



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RETURN MAPPING ALGORITHM

- **the "incremental" integration of the rate-independent elastoplastic model in either over a time step is regarded as a strain-driven process in which the total strain is the basic independent variable**

- **The integration process is local in space, that is, it takes place atspecific points of the body**

$$\boldsymbol{F_{n+1}^{trial}} = \begin{cases} \leq \mathbf{0}\ \boldsymbol{elastic\ step}\ \boldsymbol{\Delta\lambda} = \mathbf{0} \\ > \mathbf{0}\ \boldsymbol{plastic\ step}\ \boldsymbol{\Delta\lambda} > \mathbf{0} \end{cases}$$

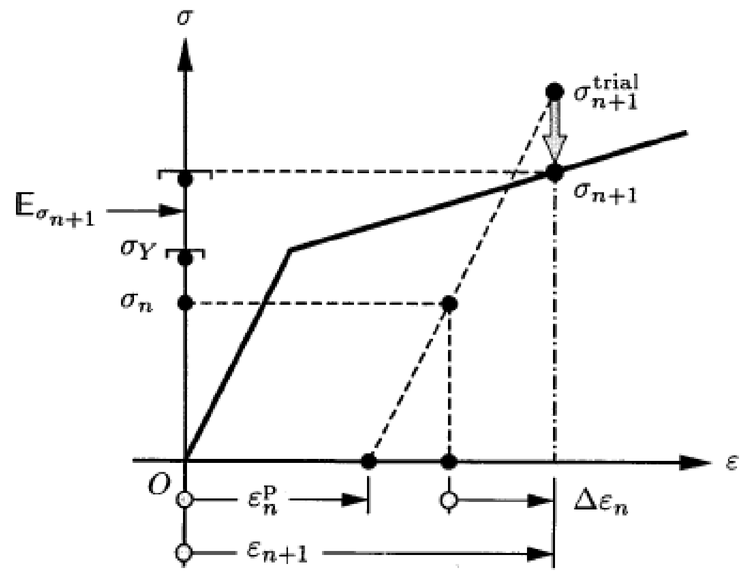

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TABLE OF CONTENTS

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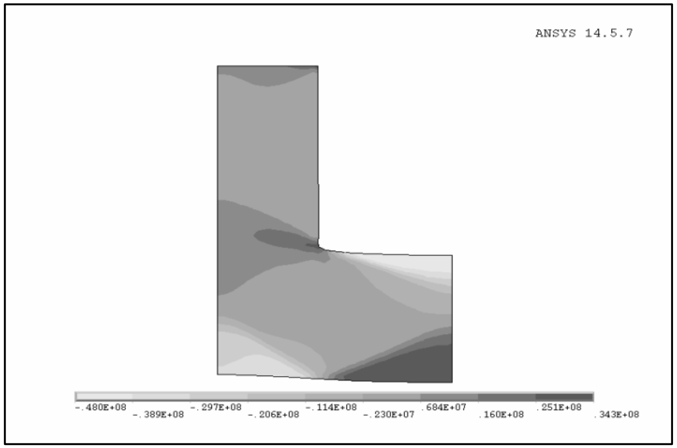
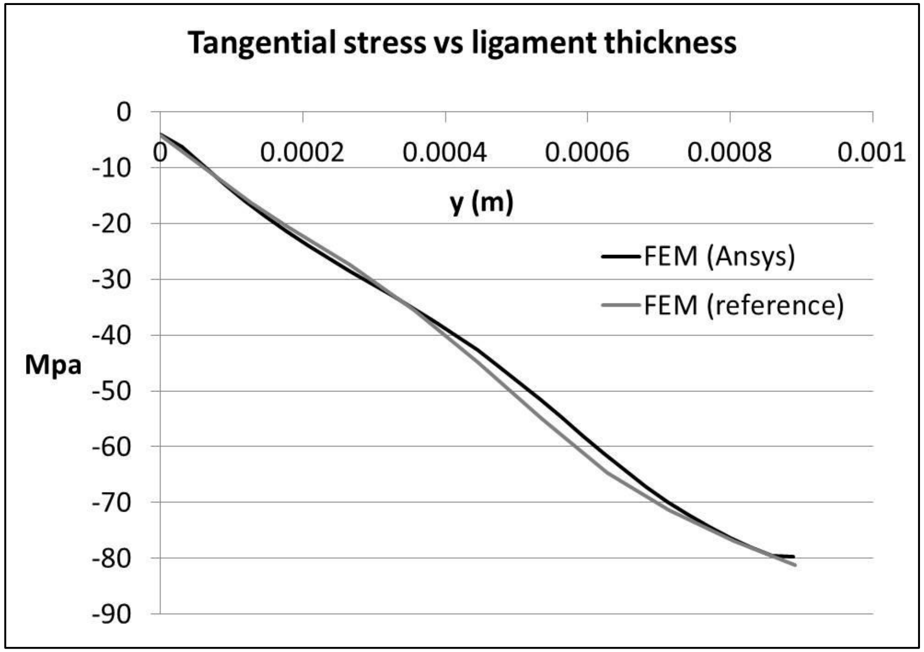
• The hoop tangential stresses are compressive during the hot phase, then the ligament yields in compression.

• During creep, the hoop stresses relax becoming tensile after about 1 second. The high temperatures occurring during the hot phase generates yielding in compression of the ligament of the cooling channel and, then, the ligament width is invariably decreased.

• The ribs act as boundaries that prohibit the ligament from decreasing in length as the temperature decreases, so that a tensile stress develops as the material cools.



The maximum percentage difference between the FE model developed in the article and the benchmark FE model is about 2%.



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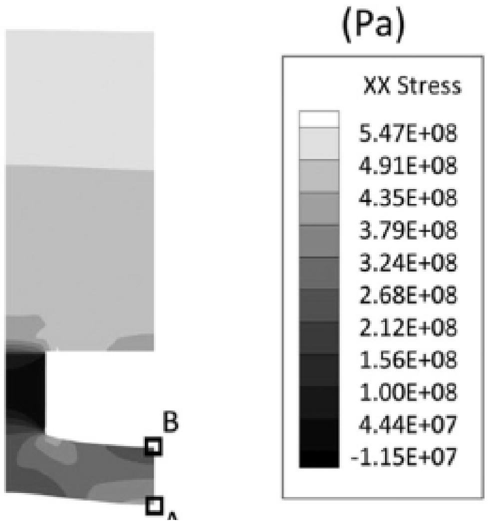
Transient thermal and static structural analysis compared with analytical model results obtained by Porowski and with Robinson's and Perzyna's viscoplastic models

Model 2=Robinson
Model 3=Perzyna

Thinning (mm) of the ligament at the end of the first 4 cycles.

	Model 2	Simplified model	Model 3
I cycle	1.80e − 2	1.78e − 2	2.04e − 2
II cycle	2.10e − 2	2.03e − 2	2.07e − 2
III cycle	2.20e − 2	2.54e − 2	2.24e − 2
IV cycle	2.37e − 2	2.67e − 2	2.45e − 2



Point B – Von Mises stress and equivalent plastic strain at the end of the cycle (3.5 s).

Point A (1.8 s)	Simplified model	Model 3	Percentage difference
Von Mises stress [MPa]	234.7	263.7	−12.4
Equivalent plastic strain	0.0393	0.0377	4.1

Point B – Von Mises stress and equivalent plastic strain at the end of the hot phase (1.8 s).

Point A (1.8 s)	Simplified model	Model 3	Percentage difference
Von Mises stress [MPa]	111.2	123.4	−11.0
Equivalent plastic strain	0.0258	0.0118	5.4

M. Ferraiuolo, V. Russo, and K. Vafai, A Comparative Study of Refined and Simplified Thermo-Viscoplastic Modeling of a Thrust Chamber with Regenerative Cooling, Int. Commun. Heat Mass Transf., 2016, 78, p 155–162

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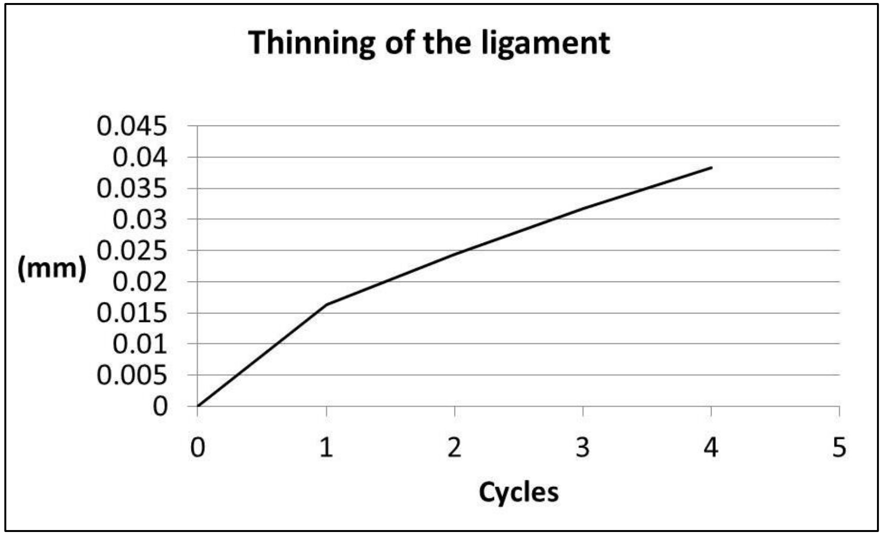
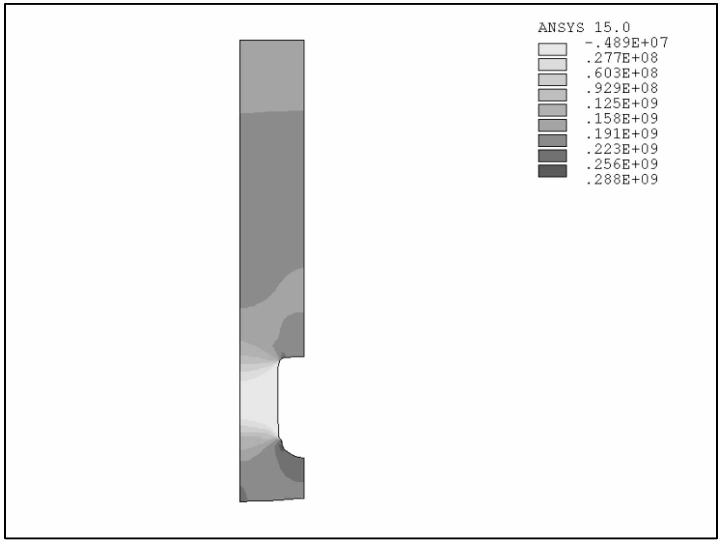
Results and Discussions

- The maximum percentage difference is about 10%
- The effects of isotropic hardening are detectable
- The FE model adopted in ANSYS is conservative
- the thinning of the ligament is significant (0.04 mm after 4 cycles)





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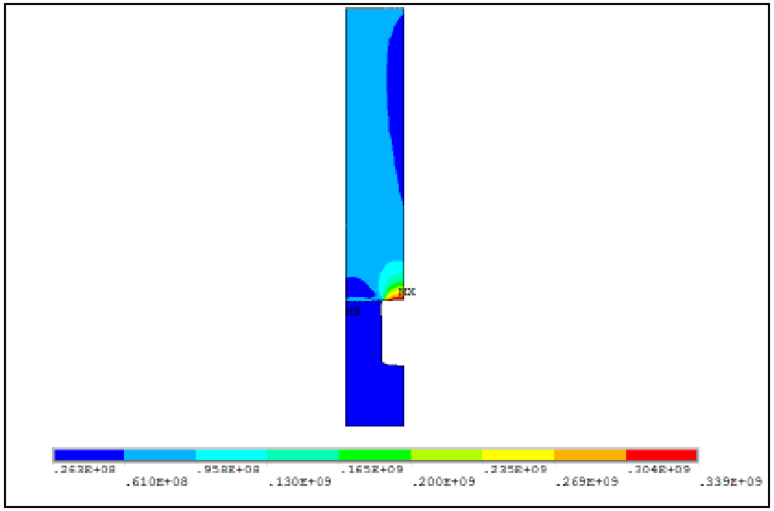
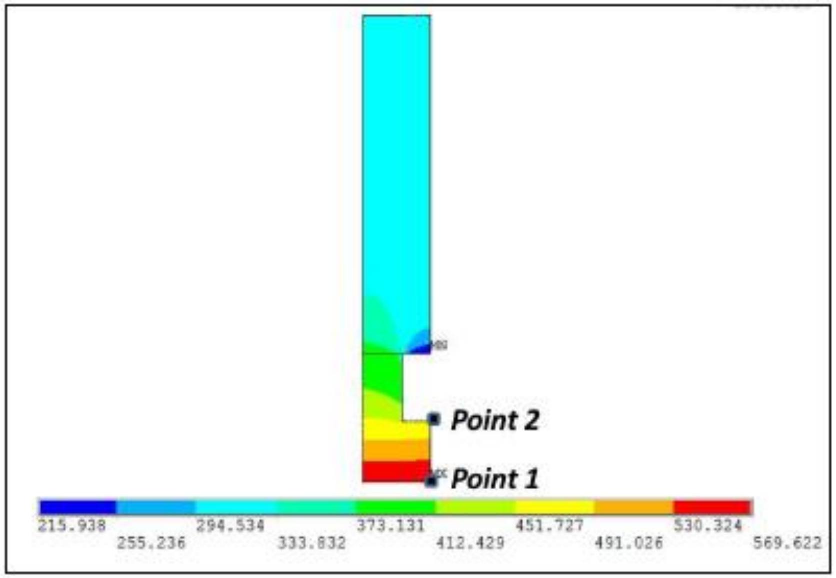
Throat section

- **Creep has been modelled**
- **"*Thermal ratcheting*" is the dominant phenomenon**
- **Tensile plastic strain accumulate cycle after cycle**
- **Failure occurs after 55 cycles with SF=4**





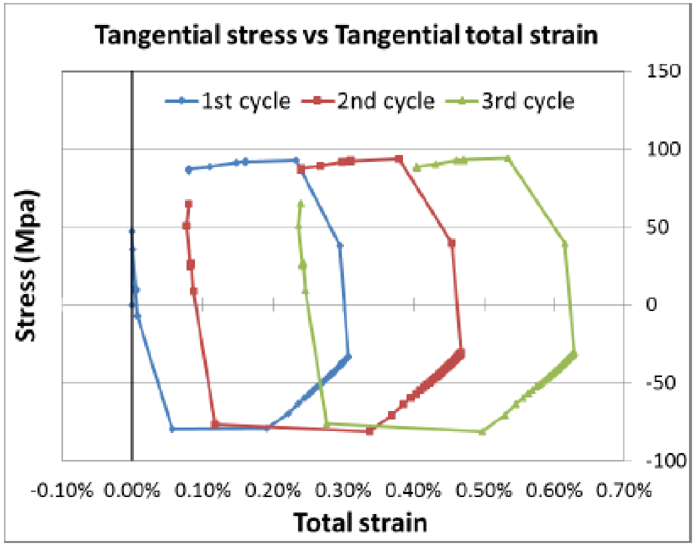


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TABLE OF CONTENTS

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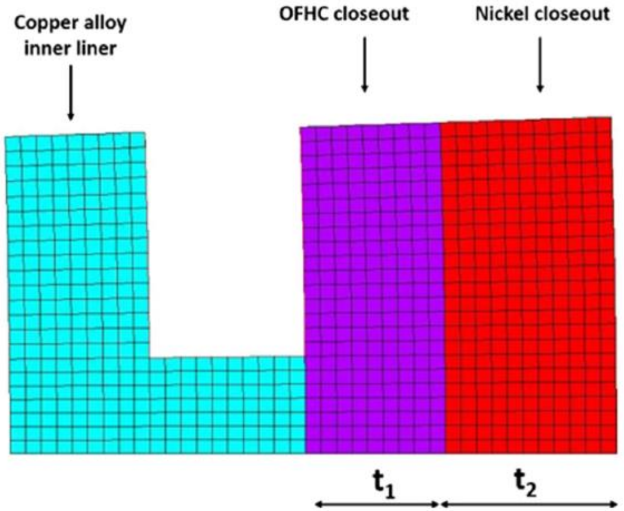
Design of the closeout

The increase in nickel closeout thickness has a beneficial effect on the service life up to 2 mm; beyond this value, a detrimental effect, even though very small, appears. More specifically, two main effects can be detected when the closeout structure becomes thicker:

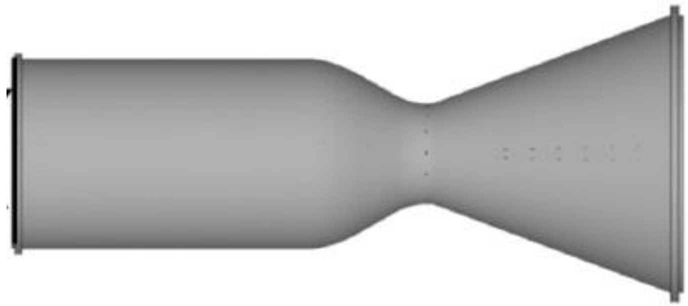
- **increase in the plastic strains, since it acts as a structural bound on the inner copper alloy structure,**
- **increase in the structural stiffness that allows to avoid excessive deformations in the ligament.**

	$t_1 = 0.5$ mm	$t_1 = 1$ mm	$t_1 = 1.5$ mm	$t_1 = 2$ mm
$t_2 = 0.5$ mm	78	70	68	65
$t_2 = 1$ mm	85	79	75	74
$t_2 = 1.5$ mm	88	82	80	79
$t_2 = 2$ mm	88	83	81	80
$t_2 = 2.5$ mm	84	81	80	79
$t_2 = 3$ mm	68	69	69	69



- **Composite materials could be very useful when applied to structural rocket engine components since they can allow significant weight savings thanks to their high specific strength and high specific stiffness.**

- **A carbon fiber reinforced composite has been adopted to replace the typical heavy metallic closeout structure of a regeneratively cooled thrust chamber of a liquid rocket engine. The composite structure has been considered wrapped over the inner liner of the thrust chamber, made of copper alloys, and provides hoop strength for withstanding the fuel/coolant pressure in the cooling channels.**



M. Ferraiuolo, W. Petrillo, and A. Riccio, On the Thermo-Structural Response of a Composite Closeout in a Regeneratively Cooled Thrust Chamber, Aerosp. Sci. Technol., 2017, 71, p 402–411

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TABLE OF CONTENTS

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Conclusions and Future Activities

- **Several works (e.g. Riccius) have demonstrated that neglecting the effects of fluid-structure interaction leads to an underestimation of the service life of the thrust chamber**
- **Then, it could be useful to develop coupled numerical analyses in order to improve the accuracy of the results**
- **Since fluid-structure interaction analyses are heavy, simplified and reducued order models (e.g. Proper Orthogonal Decomposition) can be adopted in order to obtain accurate results in a reasonable amount of time**
- **Finally, in order to further minimize CPU time, submodeling approaches together with reduced order models can be adopted. A PhD student is currently working on these aspects**

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