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A comparative study of refined and simplified thermo-viscoplastic modeling of a thrust chamber with regenerative cooling☆

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ABSTRACT

The thermostructural response of the cooling channel of a regeneratively cooled thrust chamber employed for rocket applications can be evaluated by means of analytical and numerical methods. The heat fluxes produced by the combustion inside the thrust chamber cause elevated temperatures in the copper structure composed of ligaments separating the coolant flow from the combustion gases. Those thermal loads together with the mechanical loads due to the flowing coolant and hot gases, lead to a non linear structural response. In the present work a comprehensive study of the viscoplastic phenomena is carried out and a simplified finite element model, which does not take into account strain rate-dependent effects, is adopted.

The aim of the work is twofold: understanding and detail modeling of the thermo-viscoplastic phenomena occurring in the copper inner liner of a rocket thrust chamber and evaluating the degree of importance of strain-hardening rate-dependent phenomena. The present paper demonstrates that the simplified viscoplastic model adopted in this work is suitable in the preliminary design phase since the percentage difference detected with respect to rate dependent models, such as Perzyna's and Robinson's ones, is slightly larger than 10%. Furthermore, this model is particularly useful when the results of strain hardening tests, aimed at evaluating strain rate dependent properties, are not available for the chosen material.

1. Introduction

Liquid Rocket engines for aerospace applications operate at extremely high heat fluxes (1–10 MW/m^2) and pressures (50–100 bar); as a result, the thrust chamber must be actively cooled in order to preserve the hot gas side wall from melting [1,2]. In particular, regenerative cooling, where the fuel itself acts as a coolant and is passed through the coolant channels, provided in the periphery of the chamber wall, 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.

Copper alloys are usually chosen for the inner liner of the thrust chamber since they are characterized by high thermal conductivity, which is useful to transfer heat from the combustion chamber to the coolant [3]; moreover, the mechanical properties are sufficient to withstand the thermomechanical cyclic loading encountered in the service life [4]. Since the pressure in the cooling channel is notably above the thrust chamber pressure, the inner liner is under compression, while the outer wall of the chamber is subjected to considerable hoop stresses. Moreover, the material of the inner liner is deteriorated because of the elevated temperatures occurring in the inner wall, and its thermal expansion is constrained by the cold side wall of the liner. As stress and strain levels rise and/or large temperature changes occur, the material behavior may become viscoplastic [5,6]. The theory of plasticity must be adopted when inelastic material behavior is encountered. Plasticity theories are based on the assumption that material behavior is time independent when load rates are small [7,8]. On the other hand, material behavior becomes time dependent when quick loading or high temperature values are detected. An example of time dependent inelastic phenomenon is creep. When plastic behavior is coupled with creep and hardening phenomena, viscoplastic models must be taken into account. The temperature at which creep effects become significant when designing thrust chambers is usually about 40% of the melting temperature of the material considered. Creep can be detected at stress values that are always much lower than the strength of the material considered [9,10].

Viscoplastic behavior of metallic structures are generally studied by means of unified Constitutive models that provide a means of analytically describing the response of a metallic material from the elastic through the plastic range, taking into account strain rate dependent plastic flow, creep, and stress relaxation phenomena. An example of

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unified viscoplastic method is due to Bodner and Partom [11]. The Bodner-Partom model is a unified model where:

- a flow law is defined to correlate the plastic strain rate with deviatoric stresses,
- a kinetic equation that shows a relationship between the inelastic strain rate to stress invariants taking into account the effects of temperature and internal state variables,
- evolution equations that describe the effects of kinematic and isotropic hardening.

Another unified viscoplastic model which can be found in literature is the Anand model [12]. The Anand model is classified into the group of the unified plasticity models where the inelastic deformation refers to all irreversible deformation that cannot be distinctively separated into the plastic deformation derived from the rate-independent plasticity theories and the part resulting from the creep effect. Compared to the traditional creep approach, the Anand model introduces a single scalar internal variable “s”, the resistance to deformation, that is adopted to depict the isotropic resistance to inelastic flow of the material. Another model employed is the Robinson's model, which adopts a dissipation potential to derive the flow and evolutionary laws for the inelastic strain and internal state variables. The model includes only one internal state variable which represents the kinematic hardening. The material behavior is linear elastic for all the stress levels within the dissipation potential and non linear viscoplastic for the stress levels outside.

Porowski proposed an analytical model for evaluating Hot-Gas Wall Deformation and Strain [13]. In this model strain rate dependent effects are considered. Moreover, material properties are assumed not to vary with temperature.

Perzyna's model could be regarded as the first model describing the evolution of viscous effects [14]: it is widely used in many engineering applications, due to the fact that it consists of a reduced number of parameters. A particular feature is that the model allows the stress to get over the Yield surface.

For the above mentioned models, the number of experimental tests needed to characterize the viscoplastic behavior of a metallic structure is quite substantial. Indeed, tensile and compressive tests at different temperature values as well as strain hardening, creep and relaxation experimental tests should be performed; as a result, the adoption of a simplified viscoplastic model in which a reduced number of experimental data is needed, could be useful in a preliminary design phase when not all the results of the experimental tests are available. For example, the results of strain hardening tests are often not available in the literature. As such, it is valuable to quantify the amount of uncertainty introduced in the finite element model when rate-dependent effects are ignored.

The present paper describes a Finite Element Model to be built in a commercial code (ANSYS) in order to illustrate the highly nonlinear phenomena detected in the hot components of a thrust chamber. Another aim of the present wok is to demonstrate that the adoption of a simplified viscoplastic model not taking into account strain rate dependent effects can be useful in a preliminary design phase since it can substantially reduce the computational time needed to run a complex thermostructural analysis.

The structure of this paper is organized as follows: a description of the simplified viscoplastic model, adopted in the finite element analyses, is given in the next section, while the results of the thermostructural analyses conducted on the rocket engines thrust chambers are illustrated in Section 3 together with comparisons with test cases taken from literature. In particular, the results of the analyses are aimed at justify that the simplified model can describe the typical phenomena occurring in the inner liner of a regeneratively cooled thrust chamber (dog house effect, thermal ratcheting, etc.). Finally, the conclusions are summarized in Section 4.

2. Analysis

2.1. Simplified viscoplastic model

The current simplified viscoplastic model is composed of the yield criterion, the flow rule, the hardening rule and time-dependent phenomena (creep). To characterize the stress components that induce plasticity, deviatoric stress components are defined by subtracting uniform hydrostatic normal stresses from the stress tensor. The hydrostatic stress is defined as:

$$\sigma_0 = \frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}) = \frac{1}{3}\sigma_{ii} \tag{1}$$

while S_{ij} is given by:

$$S_{ij} = \sigma_{ij} - \sigma_0\delta_{ij} \tag{2}$$

The equation given by the von Mises yield criterion identifies a yield surface. If the principal stresses lie within the yield surface, elastic behavior is encountered, while if the principal stresses fall on the yield surface, plastic deformation is detected.

The Prandtl-Reuss flow rule describes the relationship between the plastic strain increment and the deviatoric stresses. In particular, an increment in strain $d\varepsilon$ can be decomposed into an elastic part $d\varepsilon^e$ and a plastic part $d\varepsilon^p$. If the material is isotropic, it can be assumed that the plastic strain increments $d\varepsilon_{ij}^p$ are related to the deviatoric stresses S_{ij}:

$$\dot{\varepsilon}_{ij}^{p} = \lambda S_{ij} \tag{3}$$

To establish an accurate relationship, one must identify the positive constant scalar λ, which is a plastic multiplier that determines how much plastic strain occurs and depends on the yield criterion and the possible hardening behavior. When the material is unloaded a new elastic limit, greater than the initial elastic one, will be detected. Due to the hardening phenomenon, a new elastic limit in compression, smaller than the initial one, is encountered. This phenomenon is referred to as Bauschinger effect [15].

Creep is modeled by means of the Norton's law which represents the portion of the creep curve where the creep rate remains almost constant (secondary or steady creep):

$$\dot{\varepsilon} = B\sigma^r \tag{4}$$

where:

- B and r are material constants, r is non dimensional, B is expressed in $[1/s(MPa)^r]$
- $\dot{\varepsilon}$ is the strain rate

2.2. Thrust chamber geometry and boundary conditions

The geometry of the thrust chamber cross section is shown in Figs. 1 and 2, the thermo-mechanical load cycle history is depicted in Fig. 3. Hot gas side adiabatic wall temperature, coolant side bulk temperature with corresponding heat transfer coefficients and pressures are summarized in Table 1. The material adopted for the liner is Narloy-Z, while that adopted for the close-out is Electroformed Copper (EF copper). Tables 2 and 3 illustrate the thermal and mechanical properties adopted for the thermo-mechanical analyses [16]. The benchmark chosen for the comparison is characterized by relevant creep phenomena. The pressure differential between the coolant and the hot gases flows is 20.68 MPa and the hot phase lasts 240 s. As a consequence creep strains

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