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Thermostructural Analysis of Rocket Engine Thrust Chamber

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Abstract: **High performance rockets are developed using cryogenic technology. High thrust cryogenic rocket engines operating at elevated temperatures and pressures are the backbone of such rockets. The thrust chambers of such engines which produce the thrust for the propulsion of the rocket can be considered as structural elements. Often double walled construction is employed for these chambers for better cooling and enhanced performance. The double walled rocket engine thrust chamber investigated here has its hot inner wall fabricated out of a high thermal conductive material like copper alloy and outer wall made of stainless steel. Inner wall is subjected to high thermal and pressure loads during operation of engine due to which it will be in the plastic regime. Major reasons for the failure of such thrust chambers are low cycle fatigue, creep and thermal ratcheting. Elasto plastic material models are required to simulate the above effects through a cyclic stress analysis. This paper gives the details of cyclic stress analysis carried out for a block using the Chaboche nonlinear kinematic hardening plasticity model. The reliable results available from the block is used for the analysis of thrust chamber.**

1. INTRODUCTION

Thrust chamber is one of the main components of a cryogenic rocket engine. It is the subassembly of rocket engine in which propellants are injected, mixed and burned to form hot gas products which are accelerated and ejected at high velocity. The thrust chamber investigated in this work is double walled and regeneratively cooled using Liquid Hydrogen. The inner wall of the thrust chamber is made up with a special copper alloy whereas the outer wall is fabricated from stainless steel.During operation, both the walls experience severe thermal and pressure loads. The inner copper wall has to take care of two contradictory functional requirements. The wall thickness has to be optimised to offer least resistance for heat transfer rate and thereby limit thermal gradients. The inner wall also should have sufficient thickness to withstand the pressure and mechanical loads exerted by coolant pressures and combustion gas pressures. Normally an engine has to undergo repeated cycles of operation before putting to actual use in the flight. Hence cyclic stress analysis of the thrust chamber is of paramount importance so that its structural integrity during flight is ensured. Stress analysis predicts the manner in which a mechanical component will perform structurally under anticipated working conditions. The goal is to design an element with sufficient, but not excessive, strength in every detail. Cyclic stress analysis of a rocket engine thrust chamber using Chaboche model is reported in this work. Failure of a double walled thrust chamber occurs due to bulging and fracture of inner wall. One of the major reasons for its failure is ratchetting. Ratchetting decides the number of times the engine can be hot tested which is one of the major engine operating parameter. Chaboche model is a nonlinear kinematic hardening model which can predict ratcheting more accurately unlike the conventionally used linear kinematic hardening models and isotropic hardening models.

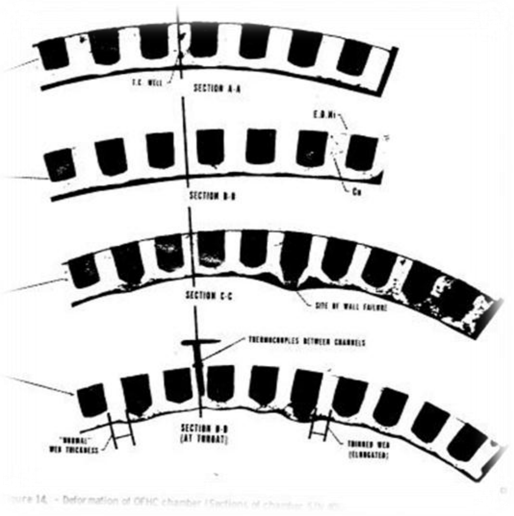

Fig. 1. Progressive failure of a double walled thrust chamber cross section

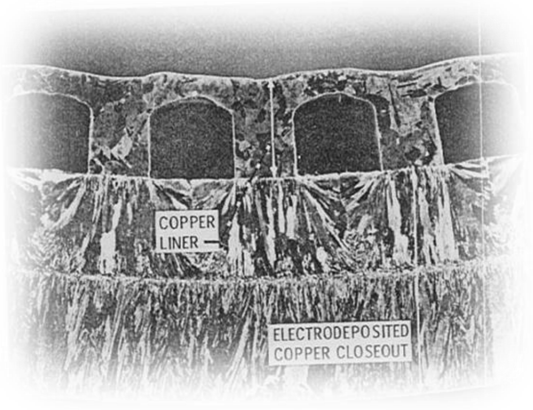

Fig. 2. Dog house effect

PLASTICITY MODELS

Development of models for in-elastic behavior of materials has been an area of substantial development over the past 20-30 years and is still a very active research area. New models are developed even recently. Today's FE codes provide models for the analysis of plastic deformation of metallic materials, even though the most recent models are yet to be implemented. Plasticity models provide a mathematical relationship that characterizes the elasto-plastic response of materials. Choice of plasticity model depends on thexperimental data available to fit the material constants

The basic requirements of a plasticity model are

- Yield criterion
- Flow rule
- Hardening rule

Conventional plasticity models are

- Linear isotropic hardening models
- Linear kinematic hardening models

Linear isotropic hardening models

These models are appropriate for large strain, proportional loading situations. They are less preferred for cyclic loading. Isotropic hardening model alone is incapable of describing a cyclic behaviour that includes repeated cyclic deformation, however these models are capable of simulating complex cyclic behaviours when combined with kinematic hardening models.

Linear kinematic hardening models

They follow a linear hardening curve in cyclic loading situations. The hardening rule is given by

$$d\alpha_{ij} = c\, d\varepsilon_{ij}^{p}$$

$\mathbf{d\alpha_{ij}}$ = incremental back stress

$\mathbf{d\varepsilon_{ij}^{p}}$ = incremental plastic strain

They can describe stable loops in cyclic loading, including the Bauschinger effect. For a prescribed uniaxial stress cycle with a mean stress, they fail to distinguish between shapes of the loading and reverse loading hysterisis curves and consequently produces a closed loop with no ratchetting.

Non linear kinematic hardening models

They follow follow a smooth non linear hardening curve in cyclic loading situations. The hardening rule is given b

$$d\alpha_{ij} = \frac{2}{3} c\, d\varepsilon_{ij}^{p} - \gamma \alpha dp$$

α = back stress

They siimulate ratchetting and shakedown in a FEA simulation. Nonlinear kinematic hardening implies a shift (or movement) of the yield surface along a nonlinear path. It is similar to linear kinematic hardening except for the fact that the evolution law has a non linear term called recall term. Non linear kinematic hardening does not have a linear relationship between hardening and plastic strain. The non linear term is associated with the translation of the yield surface.

CHABOCHE MODEL

The Chaboche model is a type of non linear kinematic hardening model commonly used to simulate the plastic deformation of metals. It was added in ANSYS 6.0 to complement the existing isotropic and kinematic hardening rules. Chaboche model is based on von Mises yield criterion. The yield function for the non linear kinematic hardening model is

$$F = [\tfrac{3}{2}(\{S\} - \{\alpha\})^{T}[M](\{S\} - \{\alpha\})]^{1/2} - R = 0$$

$\{S\}$ = deviatoric stress tensor

$\{\alpha\}$ = back stress tensor

[M] = matrix containing information on different yield strengths in different directions

R = yield stress

Experimental data and a curve fitting tool are used to determine a set of material parameters for the Chaboche kinematic hardening model in ANSYS 15.A third order Chaboche kinematic hardening model is generally used, as it provides sufficient variation to calibrate the non linear behavior of the metal.

Chaboche model is expressed as

$$\alpha = \sum_{i=1}^{n} \alpha_i$$

$$\alpha_i = \frac{2}{3} c_i \, \varepsilon^p - \gamma_i \alpha dp$$

$\boldsymbol{\varepsilon}^{\mathbf{p}}$ = plastic strain

c, $\boldsymbol{\gamma}$ = Chaboche material parameters

The first term in the equation is the hardening modulus and the second term is the recall term that produces a non linear effect. The recall term incorporates the fading memory effect of the strain path and essentially makes the rule non linear in nature. The material parameter γ_i controls the rate at which hardening modulus decreases with increasing plastic strain.

A stable hysterisis curve can be divided into three critical segments: the initial high modulus at the onset of yielding, the constant modulus segment at a higher strain range and the transient non linear segment (knee of the hysterisis curve). Chaboche initially proposed to use three decomposed hardening rules to improve the simulation of the hysterisis loops in these three segments. He suggested that the first rule (α_1) should start hardening with a very large modulus and stabilize very quickly. The second rule (α_2) should simulate the transient non linear portion of the stable hysterisis curve. Finally, the third rule (α_3) should be a linear hardening rule ($\gamma_3 = 0$) to represent the subsequent linear part of the ratcheting curve at a high strain range. The resulting yield surface center is

$$\alpha = \alpha_1 + \alpha_2 + \alpha_3$$

Ratchetting predictions can be improved by introducing a slight non linearity in the third rule by assigning a small value to γ_3, keeping other parameters the same. This small value does not introduce any noticeable change in the strain controlled stable hysterisis loop simulation. A non zero γ_3 does not have any effect on α_1, but it changes the course of α_3 and thereby of α_2, which improve the uniaxial ratcheting simulation and prevent shakedown. The higher the value of γ_3, the third rule would reach its limiting state and, consequently, the earlier the steady rate of ratcheting would start. “Fig. 3”, shows the details of third order Chaboche model

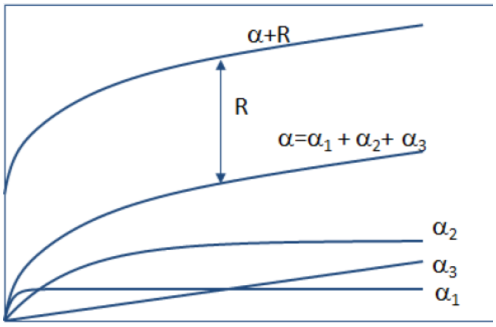

Fig. 3. Details of third order Chaboche model

CYCLIC STRESS ANALYSIS OF A SIMPLE BLOCK

Cyclic stress analysis of a simple block is carried out to simulate the cyclic hardening behaviour occuring under symmetric pressure as well as displacement loading conditions.
Analysis is done using the following models

- MISO (Multilinear isotropic hardening) model
- BISO (Bilinear isotropic hardening) model
- KINH (Multilinear kinematic hardening) model
- BKIN(Bilinear kinematic hardening) model
- Chaboche model
- MISO+ Chaboche model

Analysis is done under pressure as well as displacement loading conditions separately.

ELEMENT CHOSEN FOR ANALYSIS

To capture the cyclic behavior, a single SOLID185 element is used with quarter symmetry boundary conditions and uniaxial displacement in the Y direction. Elastic properties for copper alloy are a Young’s modulus of 110660 MPa and poisson’s ratio of 0.3. Fig 4 shows the FE model of a simple block.

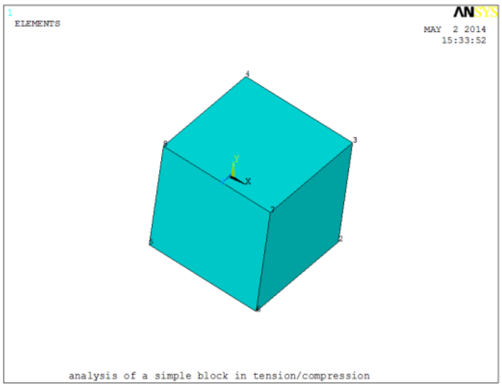

Fig 4: FE model of simple block

Non linear material properties are input via graphical user interface. Chaboche parameters for strain range ±0.75% at 900 K is used. Table 1 shows the Chaboche model parameters for copper alloy.

Stress strain points for multi linear isotropic hardening model option as well as multilinear kinematic hardening option are obtained from the tension test data for copper alloy at 900 K. Fig 7.2 shows the graph comparing true stress- true strain and and true stress-true strain fit and Fig 7.3shows the graph comparing true stress- truestrain fit and MISO curve . Table 7.2 shows the MISO points. The same points are used for KINH model. A yield strength of 76N/mm^2 and a tangent modulus of 3000 N/mm^2 is taken for BISO and BKIN models.

Sl no	True strain	True stress
1	0.00053576	76
2	0.019	88
3	0.035	96
4	0.045	100
5	0.1	111
6	0.13	115
7	0.17	120
8	0.26	127
9	0.3	129
10	0.4	134
11	0.7	144
12	0.92	150

Table 1: Chaboche model parameters for copper alloy

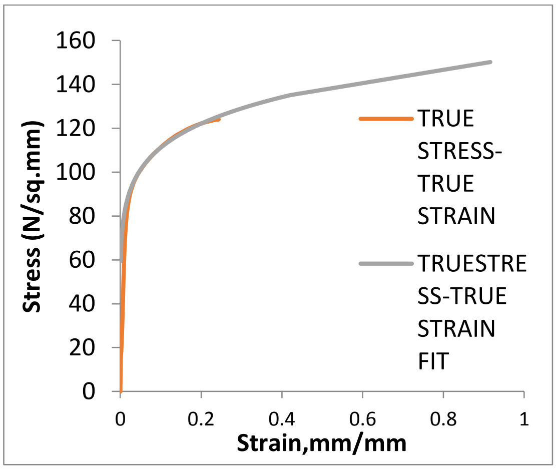

Fig 5: Graph comparing true stress- true strain

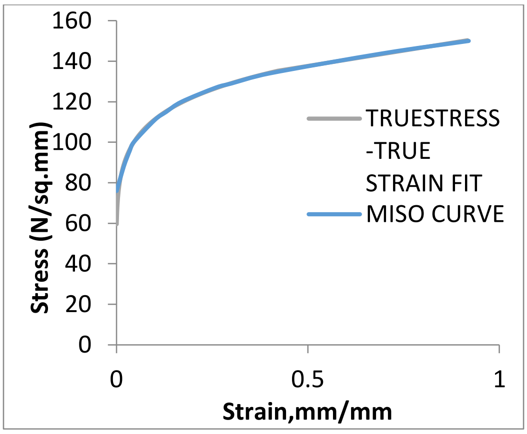

Fig 6: Graph comparing true stress- true and true stress-true strain fits train fit and MISO curve

Sl. No.	Parameter	Final value
1	C_1	329433.77
2	γ_1	200987.64
3	C_2	40220.46
4	γ_2	1107.84
5	C_3	163.77
6	γ_3	9
7	σ_o	32

Table 2: MISO points

CYCLIC STRESS ANALYSIS RESULTS

Different stress strain graphs were obtained as a result of the cyclic stress analysis conducted on a simple block. The Figures given below show Axial stress-strain variation.

PRESSURE LOADING

MISO model

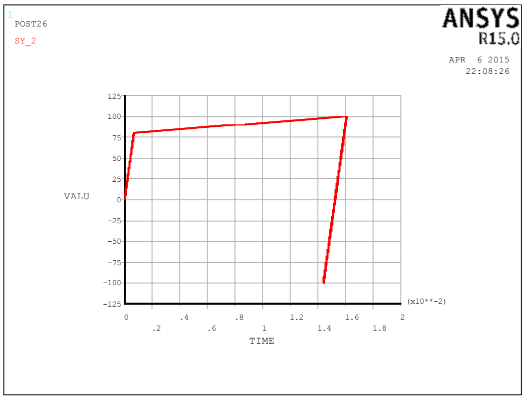

Fig 7 :Axial stress- strain variation

MKIN model

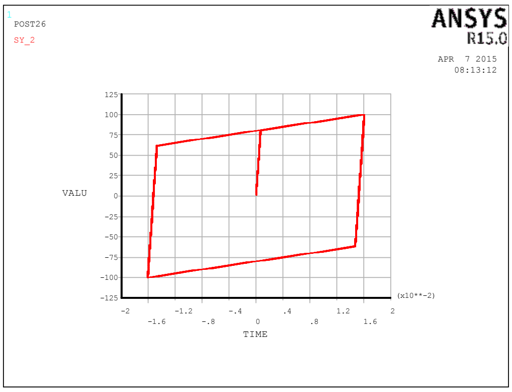

Fig 8 :Axial stress- strain variation

BISO model

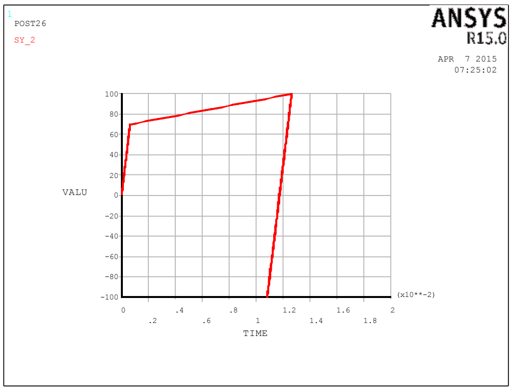

Fig 9 :Axial stress- strain variation

BKIN model

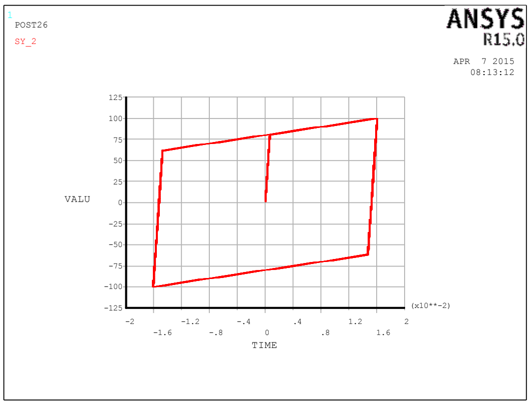

Fig 10 :Axial stress- strain variation

DISPLACEMENT LOADING

MISO model

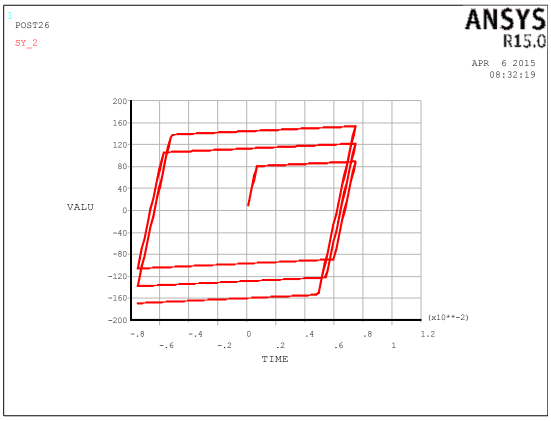

Fig 11 :Axial stress- strain variation

KINH model

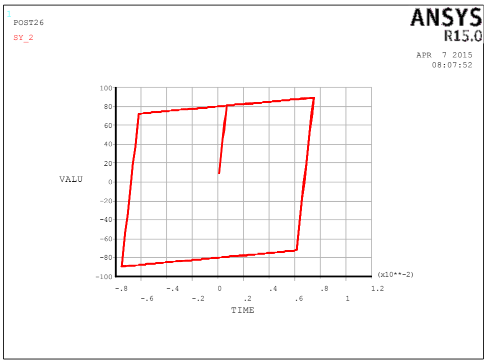

Fig 12 :Axial stress- strain variation

BISO model

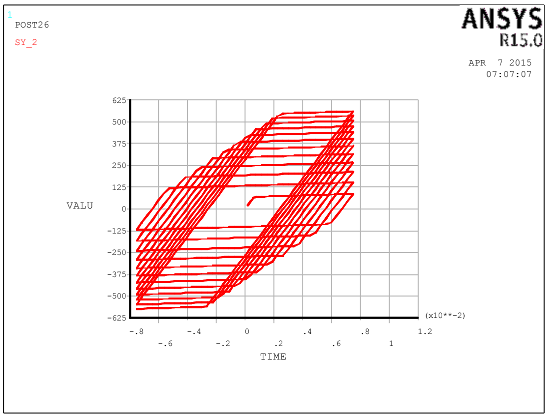

Fig 13 :Axial stress- strain variation

BKIN model

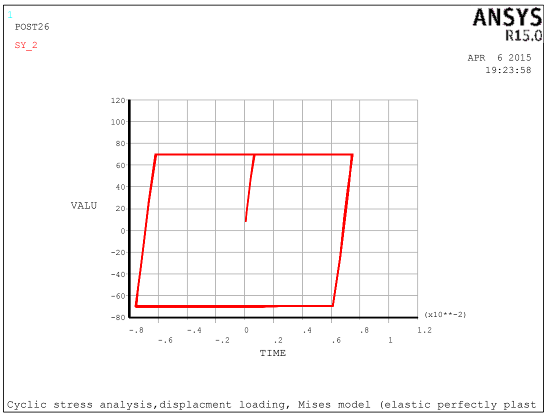

Fig 14 Axial stress- strain variation

CHABOCHE MODEL

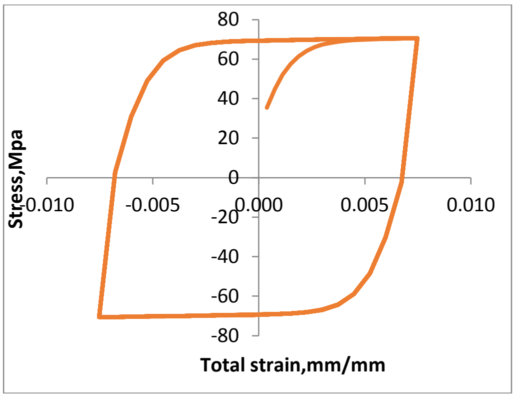

Fig 19 :Axial stress- strain variation

MISO + Chaboche model

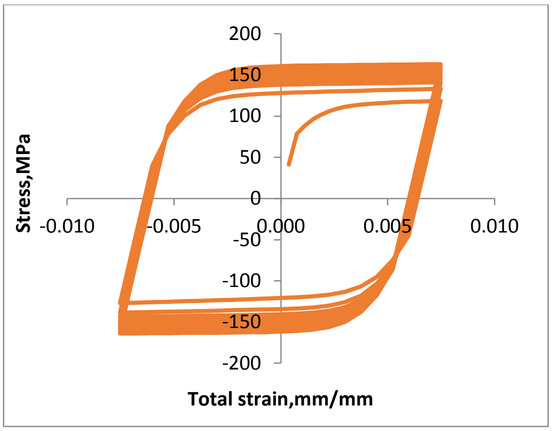

Fig 20 :Axial stress- strain variation

OBSERVATIONS

FOR PRESSURE LOADING

- MISO model did not show cyclic response
- KINH model beautifully (nonlinear fashion) showed cyclic responseBISO model did not show cyclic response
- BKIN model showed cyclic response in linear fashion. No cyclic hardening
- Chaboche showed non linear cyclic response
- MISO + Chaboche showed cyclic response with cyclic hardening

FOR DISPLACEMENT LOADING

- MISO model showed cyclic hardening in linear fashion
- KINH model showed cyclic response in a linear manner but did not show any cyclic hardening
- BISO model showed cyclic hardening in linear fashion
- BKIN model showed cyclic response in linear fashion. No cyclic hardening
- Chaboche showed cyclic response clearly, Cyclic hardening was not observed
- MISO +Chaboche showed cyclic response clearly, Cyclic hardening was observed

DISCUSSION

MISO + Chaboche model is the best model considered for simulating the cyclic hardening behaviour. All other models considered is not able to capture the behaviour properly. Cyclic hardening is a complex material behaviour with expansion and translation of yield surface. MISO model captures yield surface expansion whereas Chaboche model captures yield surface translation. Non linear response of chaboche model is due to the two additional non linear rules present compared to other models. Based on the studies conducted on MISO+CHAB model under displacement loading conditions, it is seen that, (CHAB stabilized stress – yield strength) + MISO stabilized stress = (MISO+CHAB) stabilized stress .Studies conducted using MISO+CHAB models under pressure loading conditions indicate the ineffectiveness of MISO model except for its help in cyclic hardening modelling. MISO+CHAB model starts with CHAB pattern initially and subsequently shows hardening trend .

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