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DAMAGE OF THERMO-ELASTO-PLASTIC MULIMATERIAL UNDER THERMAL CYCLING CONDITIONS

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ABSTRACT

The increasing of the temperature in the multi-material solicited with thermal and mechanical charges leads to surpass the load of elastic constraint, so we have to apply the thermo-elasto-plastic behavior.

The increasing need of structures having multiple functions orientates designers to combine materials in order to obtain, according to coupling scales, multi-materials structures.

The lifetime of these structures represents a one of the main decisive element for offices and manufacturers studies. The results of this work should be added to the set of functional charges to obtain an optimal and final decision on the design of the product.

In this study, a numerical analysis conducted by finite elements method of thermo-elasto-plastic behavior of these type of materials and their damage under thermal cyclic solicitations. The study is led in two dimensions (r, z) on a cylindrical material constituted of two layers (stainless steel, Steel), subjected to a variable heat flux at the internal surface and an exchange with the ambient at the external surface. Other faces are isolated. The sample is fixed in the axial direction and free in the radial direction. The damage model is based on the works of Lemaître and Chaboche.

Numerical results are presented for periodic heat flux and for different thickness of the material. The study is concluded by optimizing of the thickness of materials according to the total lifetime caused by thermo-elasto-plastic effect

INTRODUCTION

The performance of many thermal systems (boiler, reactor, motors, turbines, transport system, etc....). Passes necessarily by the knowledge and the optimization of the principal elements which constitute it. Indeed, according to the frequency of the use of these systems, some of its components are more or less requested either by thermal and/or mechanical effect.
A study of the thermo-mechanical coupling of these systems is thus necessary for an optimal forecast of their lifespan in term of damage in operation mode.

Few works have been devoted to a local study of damage in the composites in transient state under variable thermal conditions in space as well as on time. Indeed, most of studies have been realized in steady thermal state [1] or in unsteady state by supposing a negligible thermal resistance to each instant [2]. In general manner, these approaches underestimate the thermo-elasto-plastic behavior of these materials and as a result their behavior in fatigue [3].

In the scientific field, the main existing laws of damage [4] are applied only on homogeneous materials.
The application of these laws of damage in the case of composite or multi-layer materials thus requires a correct homogenization based on criteria of equivalence which can thermal or mechanics between exact material and homogeneous material.

It is also evident that in a tow- layer material, there is a mutual influence of one material on the other; we cannot have an abrupt variation of the thermal and mechanical properties at the level of the joining. At this level, we have a certain region in which the values of thermal and mechanical properties are supposed to vary between those of the constituted materials.

This reasoning imposes the necessity of the research for a method of correction based on the principle of homogenization of multi-materials in a single equivalent material. This latter has to undergo the study of the damage under thermo-mechanical constraints [11].

The homogenization approach proposed in [6] replaces the multi-material with a unique material having constant and equivalent thermo-physical properties obtained by means of models that allow us to have similar temperatures in both materials and in equivalent materials as well.

In this article, we're carrying out an analysis of the damage in two layer isotropic materials (stainless steel, steel) in the transient state. The body is submitted to a thermal cycling heat flux on one face and an exchange by convection with ambient in the opposite face.

This work is organized as follows: A description of the studied sample is detailed in section I, the physical formulation of the thermo-mechanical problem is shown in the section II. Section III contains the numerical analysis of this work, and in section IV, we present and analyze the obtained results for elastic, plastic and damage regimes. The conclusion of this paper is given in section V.

NOMENCLATURE

Symbols:

B_0 constant of the damage law (MPa)
C calorific capacity, J/Kg k
E module of elasticity, Pa
e_i thickness of the layer i (i=1,2)
e thickness of the body ($e = e_1 + e_2$)
h coefficient of convection, W/m2 K
K_y coefficient of plastic resistivity MPa
L length m
M_y exponent of work hardening
Q density of flux, W/m2
r radial coordinate, m
T temperature, K
$T0$ initial temperature, K
U displacement according to r, m
V displacement according to z, m
z axial coordinate, m

Greek letters:

α expansion coefficient, m/K
β exponent of the damage law
ρ density, Kg/m3
λ thermal conductivity, W/m K
ν poison coefficient
σ constraint tensor, Pa
$\bar{\sigma}$ average constraint tensor, Pa
σ_l limit constraint tensor, Pa
σ_M maximum constraint tensor, Pa
σ_s constraint tensor, Pa
σ_u ultimate constraint tensor, Pa
σ_y elastic limit constraint, Pa
ε deformation tensor
ε_e elastic deformation tensor
ε^p plastic deformation tensor
ε^{th} thermal deformation tensor
ε^c creep deformation tensor

I- PRESENTATION OF THE PROBLEM

The studied body consists of two layers of different materials, the first layer is made of stainless steel and the second is made of Steel, figure 1. The physical specifications of these two materials are supposed constants, table 1.

The cylinder is submitted to a periodic heat flux Q(z,t) at the internal surface and cooled by heat convection (h, Ta) at the external surface. The other surfaces are isolated. The equivalent material is presented in figure 2.

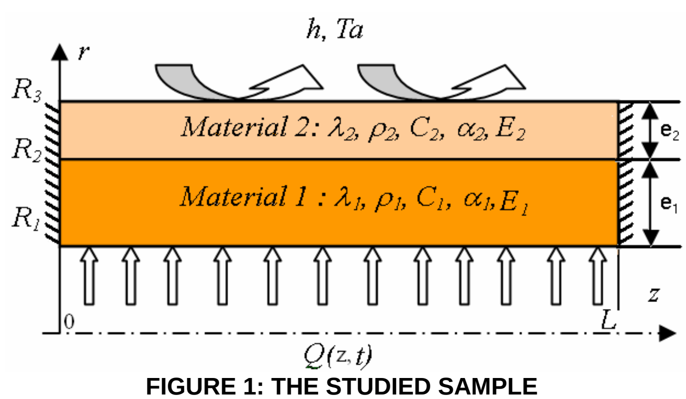

FIGURE 1: THE STUDIED SAMPLE

	Stainless steel	Steel
ρ: density	7854 kg/m3	7854 kg/m3
c: heat capacity	477 J/Kg.°K	434 J/Kg.°K
λ: thermal conductivity	35 W/m°K	60.5 W/m°K
E: young modulus	210 GPa	220 GPa
ν: poison coefficient	0.29	0.29
L: length	0.6 m	0.6m
e: thickness	$e_1 = 0.04$ m	$e_2 = 0.02$ m

TABLE 1: PHYSICAL SPECIFICATIONS OF MATERIALS [7]

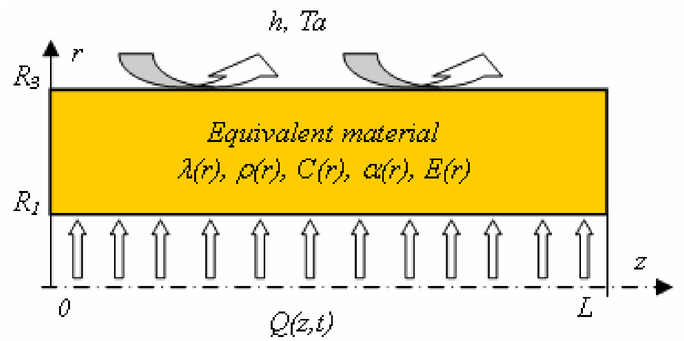

FIGURE 2: EQUIVALENT MATERIAL

II- MATHEMATICAL FORMULATION

II.1- Thermal Formulation

In the thermo mechanical coupling system, the general form of transient heat transfer balance equation [4], [9], [10] is:

$$\rho C\dot{T} = div(\lambda \, \overrightarrow{grad}\, T) + \sigma : \dot{\varepsilon}^p - A_k \dot{V}_k + r + T\left[\frac{\partial \sigma}{\partial T} : \dot{\varepsilon}^e + \frac{\partial A_k}{\partial T}\dot{V}_k\right] \quad (1)$$

Where $\varepsilon = \varepsilon^e + \varepsilon^p$ (2)

In this equation, the term:

$\sigma : \dot{\varepsilon}^p$ represents the plastic energy

$T\dfrac{\partial \sigma}{\partial T} : \dot{\varepsilon}^e$ represents the energy of thermo-mechanical coupling

r represents the internal heat production created by external sources.

$A_k \dot{V}_k$ represents the non recoverable energy stored in the material.

$T\dfrac{\partial A_k}{\partial T}\dot{V}_k$, represents the variation of the non recoverable energy stored in the material with the temperature.

In this study, we have neglected the last three terms r , $A_k \dot{V}_k$ and $T\dfrac{\partial A_k}{\partial T}\dot{V}_k$.

Indeed, for the metallic materials, the energy belongs to the residual micro-constraint filed [4], constitutes only 5 to 10 % of the value of $\sigma : \dot{\varepsilon}^p$.

II.1.1 Theoretical materials: Under these hypotheses, the theoretical thermal model of the studied system is:

$$(\rho c)_i \cdot \frac{\partial T_i}{\partial t} = div(\lambda_i \, \overrightarrow{grad}\, T_i) + T_i \frac{\partial \sigma_i}{\partial T} : \frac{\partial \varepsilon_{ei}}{\partial t} + \sigma_i : \frac{\partial \varepsilon_{pi}}{\partial t}, \quad i = 1, 2 \quad (3)$$

$i = 1$ (Stainless steel), $i = 2$ (Steel)

Boundary conditions:

$$-\lambda_1 \frac{\partial T}{\partial r} = \phi(z,t) \qquad r = R_1$$

$$-\lambda_2 \frac{\partial T}{\partial r} = h(T(r,z,t) - T_f) \qquad r = R_3 \quad (4)$$

$$-\lambda_i(z)\left.\frac{\partial T}{\partial z}\right|_{z=0} = -\lambda_i(z)\left.\frac{\partial T}{\partial z}\right|_{z=L} = 0, \quad i = 1, 2, \quad R_1 < r < R_3$$

Interface conditions: $-\lambda_1 \dfrac{\partial T}{\partial r} = -\lambda_2 \dfrac{\partial T}{\partial r}, T_1 = T_2, \ r = R_2$ (5)

Initial conditions: $T(r,z,t) = T_0$ at $t = 0$

II.1.2 Homogeneous material: For the homogeneous material, the heat balance equation is as follows:

$$(\rho c)(r)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda(r)\frac{\partial T}{\partial r}) + \frac{\partial T}{\partial z}(\lambda(r)\frac{\partial T}{\partial z}) + T\frac{\partial \sigma}{\partial T} : \frac{\partial \varepsilon_e}{\partial t} + \sigma : \frac{\partial \varepsilon_p}{\partial t} \quad (6)$$

Boundary conditions:

$$-\lambda(R_1)\frac{\partial T(R_1,z,t)}{\partial r} = \phi(z,t), \qquad r = R_1$$

$$-\lambda(R_3)\frac{\partial T(R_3,z,t)}{\partial r} = h(T(R_3,z,t) - T_0), \ r = R_3 \quad (7)$$

$$-\lambda(r)\left.\frac{\partial T}{\partial z}\right|_{z=0} = -\lambda(r)\left.\frac{\partial T}{\partial z}\right|_{z=L} = 0, \qquad R_1 < r < R_3$$

Initial conditions: $T(r,z,t) = T_0$ at $t = 0$.

II.2- Thermo-elastic regime

- Hypotheses: The body is supposed fixed in the z direction; the constraint is then unidirectional. *L/R<<45, w*e can eliminate the constraint σ_{rr}. So we have no flexion in our model and the maximum constraint is shown in the fixed and isolated sides, z=0, z=*L*.

The thermo-mechanical equation in the elastic region is obtained by the introduction of the thermal deformation in the Lame mechanical equation [7].

$$\sigma(r,z,t)_{ij} = E(T)_{ij}(\varepsilon_{ij} - \alpha_{ij}(T(r,z,t) - T_0)) \qquad (8)$$

For the theoretical isotropic material, the equation (8) can be written in the matrix form, $\alpha_{rz} = 0$:

$$\begin{bmatrix}\sigma_{rr}\\ \sigma_{zz}\\ \sigma_{rz}\end{bmatrix}_i = \frac{E_i}{(1+\upsilon)(1-2\upsilon)}\begin{bmatrix}1-\upsilon & \upsilon & 0\\ \upsilon & 1-\upsilon & 0\\ 0 & 0 & \frac{1-2\upsilon}{2}\end{bmatrix}_i \begin{bmatrix}\varepsilon_{rr} - \alpha(T(t)-T_0)\\ \varepsilon_{zz} - \alpha(T(t)-T_0)\\ \varepsilon_{rz}\end{bmatrix}_i, i=1,2 \qquad (9)$$

And for the homogeneous isotropic material, we have the matrix form, $\alpha_{rz} = 0$:

$$\begin{bmatrix}\sigma_{rr}\\ \sigma_{zz}\\ \sigma_{rz}\end{bmatrix} = \frac{E}{(1+\upsilon)(1-2\upsilon)}\begin{bmatrix}1-\upsilon & \upsilon & 0\\ \upsilon & 1-\upsilon & 0\\ 0 & 0 & \frac{1-2\upsilon}{2}\end{bmatrix} \begin{bmatrix}\varepsilon_{rr} - \alpha(T(t)-T_0)\\ \varepsilon_{zz} - \alpha(T(t)-T_0)\\ \varepsilon_{rz}\end{bmatrix} \qquad (10)$$

II.3- Plastic Formulation

In the plasticity regime, the deformation of the material is formulated by the Ramberg-Osgood equation [4]:

$$\varepsilon^p = \left\langle \frac{\sigma_s - \sigma_y}{K_y} \right\rangle^{M_y} \qquad (11)$$

Where σ_s is the applied constraint, σ_y is the elasticity limit constraint, K_y is the plastic resistance coefficient, M_y is the exponent of work hardening.

The parameters K_y, M_y and σ_y are defined in table 2

Material	σ_y (MPa)	M_y	K_y (MPa)
Stainless steel	133	4.5	435
Steel	1200	3.1	3340

TAB. 2 – PLASTICITY CHARACTERISTICS [4]

$\varepsilon_{zz}^p = 0$, because the body is fixed in the axial direction oz.

$\sigma_s = \sigma_{zz}$, is a function of (r,z,t), and is the unique constraint applied to the body in our case.

II.3.1 Theoretical materials:

The plastic deformations of the two-layer materials are written while considering each layer separated from the other one, the intermediate deformations are equal, $\varepsilon_{rr1}^p = \varepsilon_{rr2}^p$, $\varepsilon_{zz1}^p = \varepsilon_{zz2}^p$ and the decomposition of the two-dimensional plastic deformation, according to the isotropic criteria, is written as follows :

$$\begin{bmatrix}\varepsilon_{rr}\\ \varepsilon_{zz}\end{bmatrix}_i^p = \begin{bmatrix}\left(\frac{\sigma_{zz_i} - \sigma_{yi}}{K_{yi}}\right)^{M_{yi}}\\ 0\end{bmatrix}, \; i=1,2 \qquad (12)$$

The parameters σ_{yi}, Kyi, Myi , depend on the material, *i=1* (stainless Steel), *i=2* (Steel)

II.3.2 Homogeneous material:

Using the homogeneous principle, the plastic deformation, in this case, can be written according to the following form:

$$\begin{bmatrix}\varepsilon_{rr}\\ \varepsilon_{zz}\end{bmatrix}^p = \begin{bmatrix}\left(\frac{\sigma_{zz} - \sigma_{y}}{K_{y}}\right)^{M_{y}}\\ 0\end{bmatrix} \qquad (13)$$

The parameters σ_y, Ky, My are interpolated as a function of r

II.4- Thermo- elasto-plastic equation

When the material run over the elastic region, we can say that this material is in the inelastic phase, so the constraint applied to the model is [7].

$$\sigma_{ii} = \frac{E_{ii}}{(1+v_{ii})(1-2v_{ii})}\left[(1-v_{ii})\varepsilon_{ii} + v_{ii}(\varepsilon_{jj} + \varepsilon_{kk})\right] - \frac{E_{ii}}{1-2v_{ii}}\varepsilon_{ii}^{th} - \frac{E_{ii}}{1+v_{ii}}(\varepsilon_{ii}^P + \varepsilon_{ii}^c) \qquad (14)$$

Where: $i = r, \theta \; and \; z$

$\varepsilon_{ii} = \varepsilon_{ii}^e + \varepsilon_{ii}^p + \varepsilon_{ii}^c + \varepsilon_{ii}^{th}$ is the global deformation. (15)

$$\varepsilon_{ii}^{th} = \alpha_{ii}\Delta T(r,z,t) \qquad (16)$$

In our study, we have:

ε_{ii}^c =0, Always a rising load

$\varepsilon_{\theta\theta} = \varepsilon_{\theta\theta}^e = \varepsilon_{\theta\theta}^p = \varepsilon_{\theta\theta}^{th} = 0$, space (r, z) is our domain of work

$\varepsilon_{zz} = \varepsilon_{zz}^e = \varepsilon_{zz}^p = \varepsilon_{zz}^{th} = 0$, the two sides of the body are fixed in the z direction.

$\varepsilon_{rr} = \varepsilon_{rr}^{e} + \varepsilon_{rr}^{p} + \varepsilon_{rr}^{th}$.

For the theoretical isotropic materials, the matrix form of the equation (14) is:

$$\begin{bmatrix}\sigma_{rr}\\ \sigma_{zz}\end{bmatrix}_i = \frac{E_i}{(1+\upsilon)(1-2\upsilon)_i}\begin{bmatrix}1-\upsilon & \upsilon\\ \upsilon & 1-\upsilon\end{bmatrix}_i\begin{bmatrix}\varepsilon_{rr}\\ 0\end{bmatrix}_i - \frac{E_i}{1-2\upsilon_i}\begin{bmatrix}\alpha_{rr}(T(r,z,t)-T_l)\\ \alpha_{zz}(T(r,z,t)-T_l)\end{bmatrix}_i - \frac{E_i}{1+\upsilon_i}\begin{bmatrix}\varepsilon_{rr}^{P}\\ 0\end{bmatrix}_i, \quad i=1,2 \qquad (17)$$

And for the homogeneous isotropic material, the matrix form is:

$$\begin{bmatrix}\sigma_{rr}\\ \sigma_{zz}\end{bmatrix}_i = \frac{E(r,T)}{(1+\upsilon)(1-2\upsilon)}\begin{bmatrix}1-\upsilon & \upsilon\\ \upsilon & 1-\upsilon\end{bmatrix}\begin{bmatrix}\varepsilon_{rr}\\ 0\end{bmatrix} - \frac{E(r,T)}{1-2\upsilon}\begin{bmatrix}\alpha_{rr}(T(r,z,t)-T_l)\\ \alpha_{zz}(T(r,z,t)-T_l)\end{bmatrix} - \frac{E(r,T)}{1+\upsilon}\begin{bmatrix}\varepsilon_{rr}^{P}\\ 0\end{bmatrix} \qquad (18)$$

II.5- Damage model

We use here the Woehler-Miner [4] rule. The field of validity of this law is primarily the metal fatigue under periodic solicitations.

The curves of Woehler-miner represent the existing relation between the number of cycles to the rupture, the maximum value of the constraint σ_M and its average value $\overline{\sigma}$.

This rule is convenient to our case study. In fact, the mechanical load obtained from the applied thermal solicitations is periodical and one-dimensional along the z axis. The general formula for this rule is:

$$\frac{\delta D}{\delta N} = \frac{\sigma_M - \sigma_l(\overline{\sigma})}{\sigma_u - \sigma_M}\left(\frac{\sigma_M - \overline{\sigma}}{B(\overline{\sigma})}\right)^{\beta} \qquad (19)$$

Where: $\sigma_l(\overline{\sigma}) = \overline{\sigma} + \sigma_{l_0}\left(1 - \frac{\overline{\sigma}}{\sigma_u}\right)$ (20)

And $B(\overline{\sigma}) = B_0\left(1 - \frac{\overline{\sigma}}{\sigma_u}\right)$ (21)

σ_u, σ_l, B_0, β are defined in the following table for the two materials :

Material	σ_u (MPa)	σ_l (MPa)	B_0 (MPa)	β
Stainless steel	200	650	1144	5.5
steel	360	2005	6320	3.3

TAB. 3 – COEFFICIENTS OF THE DAMAGE RULE [4]

The equation (19) is valid only for the homogenous material. In our work, we have a composite material with two layers; the equation (19) is then applied to the equivalent material with non constant parameters:

$$\frac{\delta D}{\delta N} = \frac{\sigma_M - \sigma_l(\overline{\sigma})}{\sigma_u - \sigma_M}\left(\frac{\sigma_M - \overline{\sigma}}{B(\overline{\sigma})}\right)^{\beta} \qquad (22)$$

With σ_u, σ_l, B_0, β are function of r by this homogenous method [11].

III- NUMERICAL ANALYSIS

The numerical study is done by the finite differences method by using Matlab software following the organization chart:

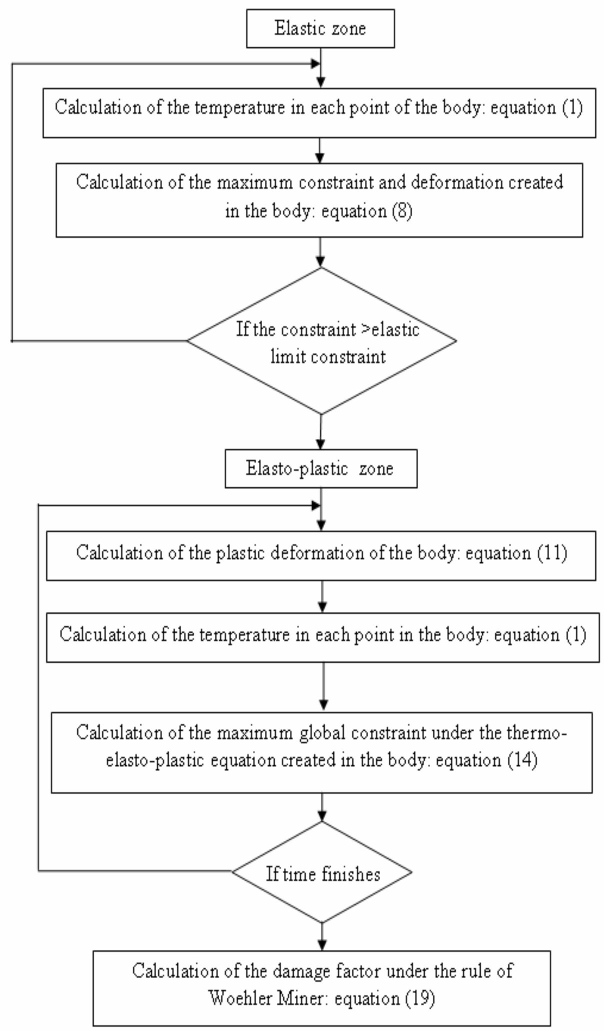

FIGURE 3: ORGANIZATION CHART

The numerical study is conducted in the conditions cited in table 1.

For the thermal problem:

$T_a = 300\ K \qquad h = 100\ W/(m^2.K)$

$$Q(z,t) = 4Q_0 z/L(1-z/L)(1+\sin(\omega t)) \qquad (23)$$

Where: $Q_0 = 12000\ \ W/m^2$, $\omega = \pi/30\ \ rd/s$

For the mechanical problem: $V(z=0)=0,\ V(z=L)=0,$

$U = V = \sigma_{rr} = \sigma_{zz} = \sigma_{rz} = 0$, at t=0.

During our study, we have calculated the temperature of the body in each point. This temperature is illustrated in figure 4 for t = 9000 s. Each curve (with a different colour) represents the variation of the temperature in a given point in the body (going from the point which is the nearest to the applied heat flux till we reach the furthest point).

We can see clearly that this temperature depends on the point of calculation according to z and r axis. This variation of the temperature with r and z axis results from the variation of the source flux in the z axis and during the time, as well as from the thermal sources resulting from the plastic and elastic deformation; see equation (1).

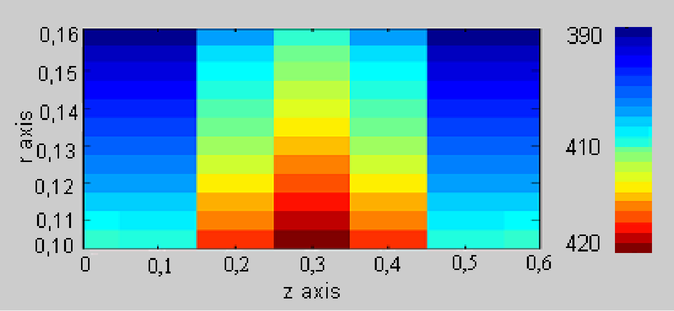

FIGURE 4: FIELDS OF TEMPERATURES AT TIME 9000 S.

IV- NUMERICAL RESULTS AND DISCUSSION

In our actual study, we take into consideration the plastic regime in addition to the elastic regime. In reality, there is an effect of the plastic and elastic deformations on the thermal formulation, as shown in the thermal sources of equation (1). This effect was not studied previously in [5]. So, to be more exact and to reflect the reality, there is a need to do the study of the thermal field, the constraints and the damage while considering these thermal sources in the formulation.

As in [5], we do a comparison between the limits of damage by considering various percentages of thickness of these two materials.

The figures 7, 8 and 9 represent the damage curves for different values of e_1 and e_2. These figures show the damage on each finite element of the material. We can see that the damage of stainless steel occurs before that of the steel, and more particularly in the face of the material where the heat flux is applied (figures 8 and 9 are more representative). Figure 10 shows the values of the inner ($r=R_1$) and outer ($r=R_2$) temperatures in the body for different values of e_1, ($e_2=l-e_1$). Figure 11 shows the value of the damage limit as a function of e_1 ($e_2=l-e_1$). From these two figures, we can conclude that for high values of the temperature in the body correspond a low resistivity and small limit damage. Contrarily when the value of the temperature is low ($e_1=e_2=0.03$ cm), the constraint in the body increases and then the damage limit is high; the body can resist more. The goal is to maximize the life time of the material with a good thermal transfer. In this study, the optimum value of e_1 corresponding to obtain this goal is *0.03* cm.

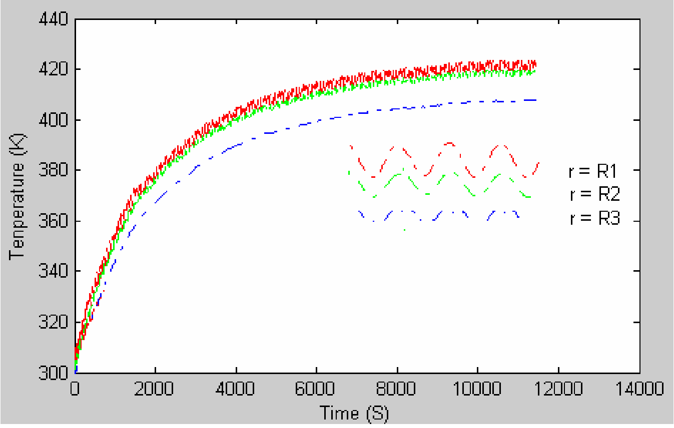

FIGURE 5: EVOLUTION OF TEMPERATURES FOR PERIODIC HEAT FLUX

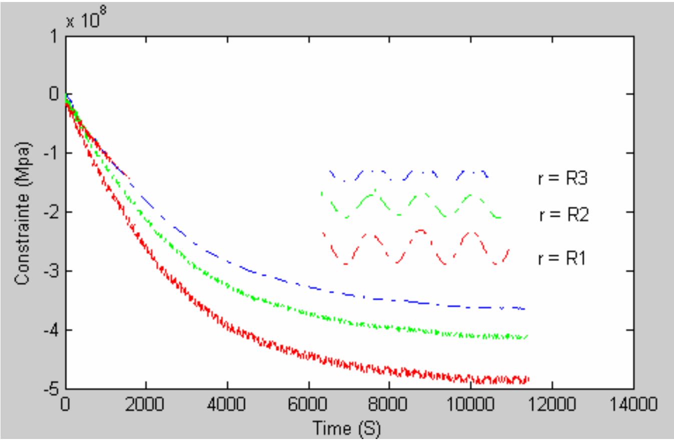

FIGURE 6: EVOLUTION OF CONSTRAINT σ_{ZZ} FOR PERIODIC HEAT FLUX

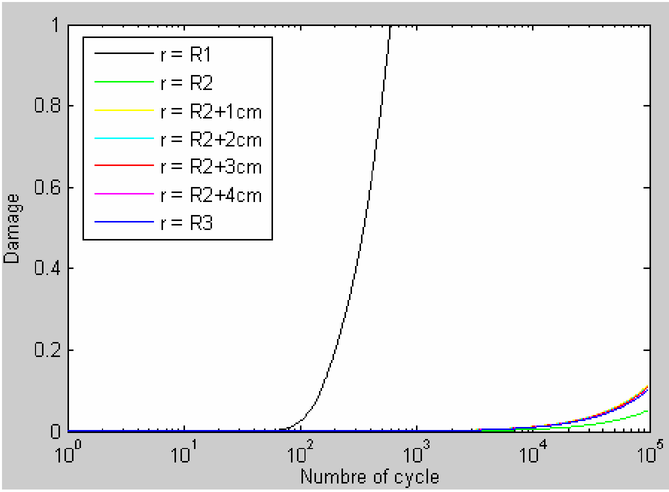

FIGURE 7: EVOLUTION OF DAMAGE FOR e_1=.01 cm AND e_2=.05 cm.

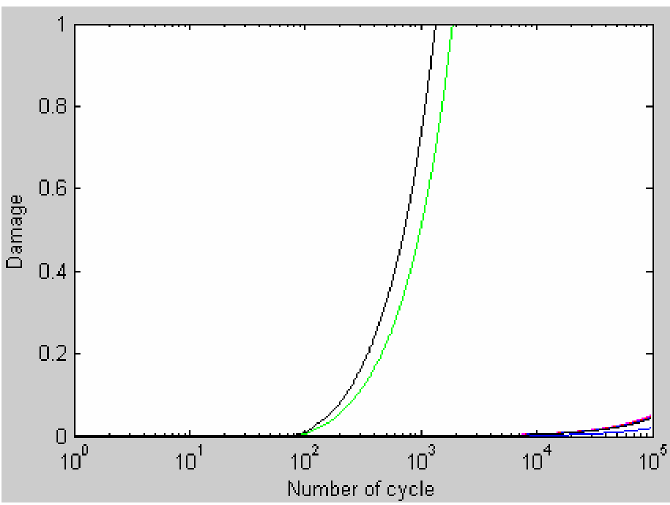

FIGURE 7: EVOLUTION OF DAMAGE FOR e_1=.02 cm AND e_2=.04 cm.

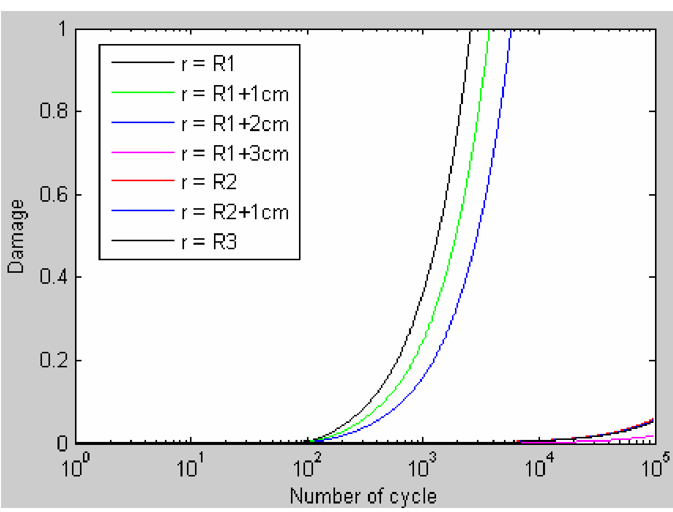

FIGURE 8: EVOLUTION OF DAMAGE FOR e_1=.03 cm AND e_2=.03 cm.

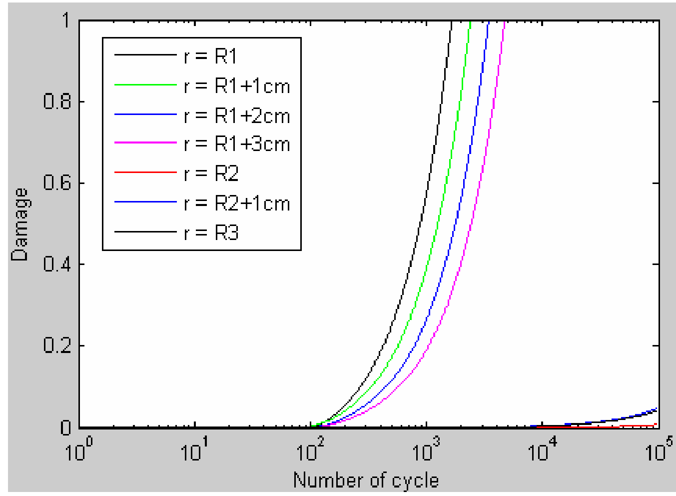

FIGURE 7: EVOLUTION OF DAMAGE FOR e_1=.04 cm AND e_2=.02 cm.

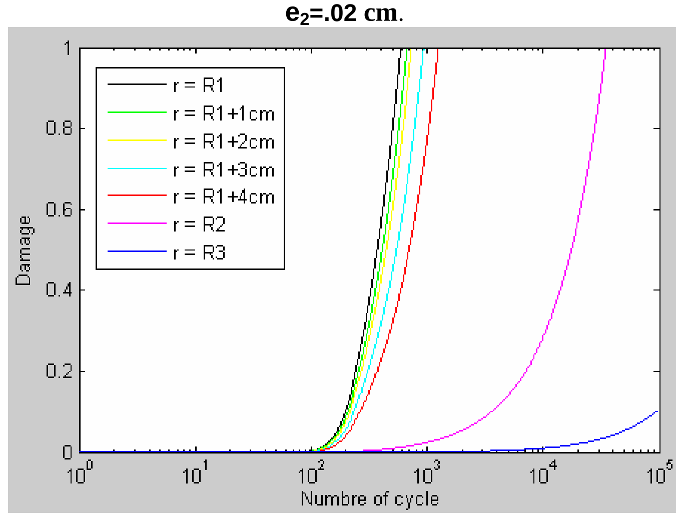

FIGURE 9: EVOLUTION OF DAMAGE FOR e_1=.05 cm AND e_2=.01 cm.

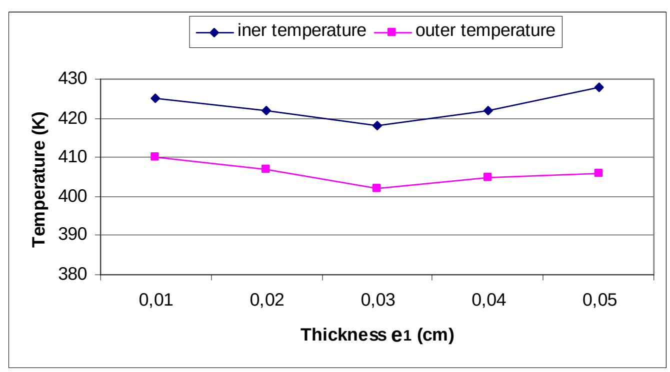

FIGURE 10: TEMPERATURE VARIATIONS IN FUNCTION OF e_1, (e_2=0.06-e_1)

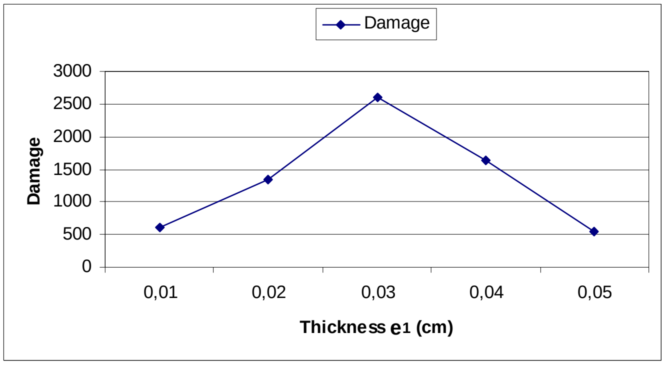

FIGURE 11: DAMAGE VARIATIONS IN FUNCTION OF e_1, (e_2=0.06-e_1)

V CONCLUSIONS AND PERSPECTIVES

In this article, we presented the results of study of the damage of multi-material in thermo-elasto-plastic regime. This damage is computed by the use of the homogenization method. The interest of the use of this method permit to calculate the damage in each point of the studied body, as well as the degree of the damage during the thermal cyclic load. So, the lifetime of the material can be analyzed.
We have seen that the distribution of the percentage of thicknesses of the constituted materials in the body has an impact to the lifetime of the whole multi-material. An optimization of this parameter is done here in the case of steel and stainless steel layers. This optimization aims to give the maximum heat transfer (low temperature values) and the maximum lifetime in the multi-material.

As perspectives to this actual work, we are interested to study the effect of the variation of the thermal solicitation's frequency on the lifetime of the multi-material, for different thicknesses of the body. Also, we will study how the shape of the thermal load (sine, triangle, rectangle…) influences the damage and the lifetime of the multi-material.

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