

J ESTIMATION FOR CRACKED CYLINDERS UNDER COMBINED THERMAL AND MECHANICAL LOADING

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ABSTRACT

In the field of non linear fracture mechanics a lot of work has been achieved for structures submitted to mechanical loadings. But for thermal loadings, and particularly for thermal shocks, only few contributions are available. We propose, here, to present the main results of a complete set of finite element computations, conducted by CEA, EDF and FRAMATOME, on cracked cylinders submitted to combined mechanical and thermal loads. The interaction between these two types of loads is analysed in the cases of austenitic and ferritic structures.

Moreover, these results are compared to the predictions obtained by simplified engineering methods (R6 procedure and two French approaches). Their domain of validity is also discussed.

KEYWORDS

Non-linear fracture, simplified engineering method, thermal and mechanical interaction

INTRODUCTION

Nuclear pressure vessels or pipings can be submitted in their life to severe mechanical and thermal loadings. In this type of structure we need engineering methods easy to apply but as accurate as possible to assess the flaws. In this paper we study the basic problem of a cylinder with an inner circumferential surface crack under combined pressure, tension and thermal gradient in the thickness. The scope here is to improve simplified rules in non-linear fracture mechanics through the understanding of the behaviour of these cylinders. After the presentation of the non-linear computational program and the simplified methods tested, we discuss the results and give some recommendations on their application.

VALIDATION PROGRAM

A set of configurations representative of the nuclear industry components have been achieved and constitute the reference data base to assess the simplified rules. The basic model is an axisymmetrically cracked cylinder (fig. 1) submitted, separately or simultaneously, to pressure : σ_p , tension: σ_{zz} , and thermal gradient in the thickness : ΔT .

The non-dimensional parameters are presented in table 1. Since the effect of pressure is studied, the load combination factors are given in table 2.

t (mm)	60				40			
R _m /t	5	10		5	10		5	
a/t	1/8	1/4	1/8	1/4	1/8	1/4	1/8	1/4

Table 1: non-dimensional parameters studied

The thermal gradient superposed to this primary loads is such as :

$$0 < \frac{E\alpha\Delta T}{2\sigma_y} < 3$$

		$\sigma_{\theta\theta} / \sigma_y$			
		0	0.4	0.8	1
σ_{zz} / σ_y	0	C9			
	0.5				C10
	0.8	C1	C3	C5	C7
	1		C11	C13	
	1.2	C2	C4	C6	C8
	1.4		C12	C14	

Table 2: Cases of primary load combinations studied

Two types of material have been taken into account : ferritic and austenitic steel, which tensile stress-strain curves are presented in fig. 2. The particularity of the first one is to present a pronounced flat plateau at the yield point.

More than thirty two-dimensional elastic-plastic (small transformations assumption) configurations have been computed with essentially two finite element codes : CASTEM 2000 for C.E.A. and ASTER for EDF.

The fracture parameter J integral is obtained using G- θ method [6],[4] validated only under the Deformation Plasticity Theory assumptions [8]. We consider that this is nearly true in our cases since J is constantly increasing.

As we deal with a thermal loading, the validation of this numerical (G- θ) method takes into account the additional area integral inside the contour : (θ is a virtual displacement field)

$$G = \int_{\Omega} (-w \operatorname{div} \theta + \sigma(\nabla u, \nabla \theta)) d\Omega - \int_{\Omega} \left(\frac{\partial w}{\partial T} (\nabla T, \theta) \right) d\Omega$$

This is true even for the thermo-elastoplastic finite element results discussed in the application part below.

SIMPLIFIED METHODS

Mechanical Loading

All the following methods to estimate J-integral (J_{R6} , J_{A16} , J_{EDF}) are based, for the mechanical part, on the plastic correction of the K_I factor using the reference stress technique as established by Ainsworth in R6 procedure [1]. This reference stress (σ_{ref}) is deduced from the limit analysis of the structure containing the defect and is given as a function of the membrane and bending elastic stresses in the flawed structure. The general scheme can be summarized under plane strain assumption by :

$$J_e = \frac{(1 - \nu^2) \times K_I^2}{E} \text{ and } J = \frac{J_e}{K_r^2} \text{ where } K_r = \frac{1}{\sqrt{\frac{L_r^3 \times \sigma_y}{2E \times \epsilon_{ref}} + \frac{E \times \epsilon_{ref}}{L_r \times \sigma_y}}} \text{ and } L_r = \frac{\sigma_{ref}}{\sigma_y}$$

where: K_I , the stress intensity factor may be obtained by finite elements or influence function method,

σ_y is the engineering yield strength

σ_{ref} is the reference stress in the cracked section

ϵ_{ref} is the reference strain corresponding to the σ_{ref} on the uniaxial tensile stress strain curve of the material.

The reference stress is deduced from one of the three following equivalent stress models :

1) beam: $\sigma_{1D} = \frac{\sigma_{1h}}{3} + \sqrt{\sigma_{1m}^2 + \left(\frac{\sigma_{1h}}{3}\right)^2}$

2) panel [9]: $\sigma_{2D} = \sqrt{0.75 \times \sigma_{2m}^2 + \left[\frac{\sigma_{1h}}{3} + \sqrt{\left(\sigma_{1m} - \frac{\sigma_{2m}}{2}\right)^2 + \left(\frac{\sigma_{1h}}{3}\right)^2}\right]^2}$

3) panel [8]:

$$\sigma_{3D} = \sqrt{\left[\frac{\sigma_{1m}^2 + \sigma_{2m}^2}{- \sigma_{1m} \times \sigma_{2m}} \right] + \left(\frac{2}{3\sqrt{3}} \right) \times \left| \frac{\sigma_{1m} \times \sigma_{1h} + \sigma_{2m} \times \sigma_{2h}}{-0.5(\sigma_{1m} \times \sigma_{2h} + \sigma_{2m} \times \sigma_{1h})} \right| + \left(\frac{2}{3} \right)^2 \left[\frac{\sigma_{1h}^2 + \sigma_{2h}^2}{- \sigma_{1h} \times \sigma_{2h}} \right]}$$

σ_{1m} and σ_{2m} are respectively axial and circumferential membrane stresses

σ_{1h} and σ_{2h} are respectively axial and circumferential bending stresses deduced from the stress distribution in the thickness of the component.

This last formula has been used for the reference stress, in the following applications, to take into account of circumferential membrane and bending stresses.

Combined Mechanical and Thermal Loading

In case of combined loading, we need first of all a classification in primary (P) and secondary (Q) stresses (for instance, thermal stresses are considered secondary) on which depends the value of the reference load. We need also a way to take into account the influence of both types of stresses. On this last point the three methods differ.

R6 procedure

For R6 procedure, K_r parameter is modified by a ρ factor which depends on L_r parameter and on the proportion of secondary and primary stresses (fig. 3) [10]:

$$J_{R6} = \frac{J_e}{(K_r - \rho)^2}$$

A16 procedure

The JA16 method introduced in the document A16 [7] proposes to take into account the difference between the nominal stresses far from the cracked section (signo) and in the ligament (sigdef). The J_e value is corrected by 2 factors: k_{1A16} related to $\text{signo}(P+Q)_{eq}$ and $\text{signo}(P)_{eq}$ (fig. 4); k_{2A16} depending on $\text{sigdef}(P+Q)_{eq}$ and $\text{sigdef}(P)_{eq}$ (fig. 5).

$$k_{1A16} = \left(\frac{\sigma_{nor}}{\text{signo}(P+Q)_{eq}} \right)^2 \text{ and } k_{2A16} = \left(\Psi_{A16} + \frac{E \times \varepsilon_{ref}}{\sigma_{ref}} \right) \text{ where } \Psi_{A16} = \frac{0.5\sigma_{ref}}{\sigma_{ref}^2 + \sigma_y^2}$$

$$J_{A16} = J_e \times k_{1A16} \times k_{2A16}$$

Moreover, when we have secondary stresses: $\sigma_{nor} \neq \text{signo}(P)_{eq}$ and Neuber extrapolation $\sigma_{ref} \neq \text{sigdef}(P)_{eq}$.

EDF procedure

As far as primary stresses are concerned, J_{EDF} method involved in the French RSE-M [2] is the same as R6 one. For the thermal stresses J_e^{th} is multiplied by the $(k_{th})^2$ factor fitted on the results of an important set of finite element computations [3] covering the domain: $0.07 \leq \frac{a}{t} \leq 0.3$ and $6 \leq \frac{R}{t} \leq 17$

$$k_{th} = \text{Min} \left[1; 0.5 + 0.5 \exp(\beta - 0.4 L_n) \right] \text{ with } L_n = \frac{E \alpha \Delta T_1}{2(1-\nu)} \times \frac{\left(1 - 5 \left(\frac{a}{t} \right)^2 \right)}{\sigma_y} < 3$$

This last formula depends on the material: for austenitic steel under linear temperature gradient $\beta = 0.32$. For ferritic steel we have $\beta = 0.44$.

Finally, mechanical and thermal terms are combined as follow:

$$J_{EDF} = \left(\sqrt{\frac{J_e^{mech}}{K_r^2} + k_{th} \sqrt{J_e^{th}}} \right)^2$$

These three procedures have been tested and compared to the finite element results.

APPLICATIONS AND COMPARISON OF THE DIFFERENT APPROACHES

Since it is impossible to give all the computational results, we have selected for the comparisons two geometries and two different materials defined as follow:

austenitic steel: $R_m = 300 \text{ mm}$; $R_m/t = 5$; $a/t = 1/4$; $E = 176 \text{ 500 MPa}$;
 $\sigma_y = 133 \text{ MPa}$; $\nu = 0.3$; $\alpha = 17.7 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$; $\lambda = 18.6 \text{ W(m.}^\circ\text{C)}^{-1}$

ferritic steel: $R_m = 400 \text{ mm}$; $R_m/t = 10$; $a/t = 1/4$; $E = 191 \text{ 837 MPa}$;
 $\sigma_y = 188 \text{ MPa}$; $\nu = 0.3$; $\alpha = 12.9 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$; $\lambda = 45.8 \text{ W(m.}^\circ\text{C)}^{-1}$

Pure thermal loading:

The gradient in the thickness, ΔT , is applied progressively from 0 to 180°C. The finite element results (fig. 6) show the elastic J_e and elastic-plastic J solution in terms of J-integral. When the yield stress is exceeded the plastic solution becomes lower than the elastic J_e . This is due to the relaxation of the thermal stresses since the strain is imposed. The comparison with the simplified methods is given in fig. 7. J_{EDF} curve is the closest from elastic-plastic solution. JA16 method gives results reasonably conservative.

Pressure and tension:

As far as pure mechanical loading is concerned we have chosen to present here the case: $\sigma_{\theta\theta} = 0.8 \times \sigma_y$ (internal pressure $\sigma_{p1} = 23.8 \text{ MPa}$) and $\sigma_{zz} = \sigma_y$

Plasticity effects becomes rapidly ($\sigma_{zz} > 0.7 \times \sigma_y$) very strong ($J/J_e = 10$). When we look at the simplified methods results we conclude that no method predicts the right value (fig. 8). This is true particularly when the part of the pressure becomes non-negligible in the mechanical loading. That means that another stress parameter is required to complete the reference stress definition to include the effect of pressure on the limit load [5]. Here we must not neglect the circumferential bending stresses in the thickness of a thick tube.

Combined mechanical and thermal loading:

When the last mechanical loading is combined with the first thermal one, the J_e remains lower than J because the influence of the mechanical load is stronger; but the ratio J/J_e decreases below the value of 2. This is reproduced quite accurately by the JA16 and J_{EDF} methods (fig. 9) if we start from the good mechanical estimation. R6 results are not shown here because they are too conservative ($J_{R6}/J = 4$).

To complete this set of results we give the comparison of the results of the different methods for a ferritic steel. The same combined loading as above has been applied to a cracked cylinder ($R_m/t = 10$).

When the yield point is reached the plasticity correction climbs up very rapidly so that estimated J becomes higher than J-integral at the end of the application of the mechanical loading (fig. 10). J_{EDF} curve on fig 11 diverges from the finite element curve at high thermal loading level because the key curve used to represent the ferritic behaviour does not match well the stress-strain curve at high stress level.

This divergence (fig.9 and 11) can also be due to the interaction between mechanical and thermal stresses opening the crack.

CONCLUSION

When simplified methods, like R6/rev.3/option 2, are applied on cylinders submitted to combined mechanical loading, it is important to take into account in the reference stress expression, not only the opening stresses but also hoop stresses for high load level.

For ferritic steels, that exhibit a yield plateau, the approach must be improved particularly in the vicinity of the yield point, to represent the progressive plastification of the ligament.

R6/rev.3/option 2 is too conservative in the case of thermal loading combined with a primary one. The two other methods (J_{A16} and J_{EDF}) takes better into account the secondary stress relaxation while remaining conservative.

The computational program will be completed by thermal shocks, 3D computations of semi-elliptical flaws under bending and thermal stresses, and on other cracked structures submitted to primary and secondary loads. The improved simplified methods will also be applied and assessed for these more realistic configurations.

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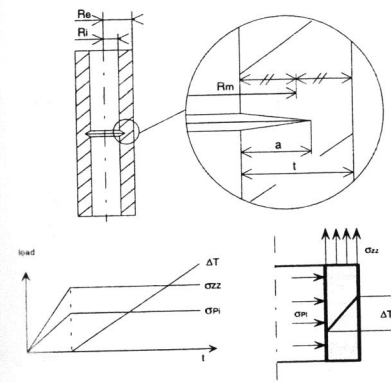


Fig. 1 : Loadings on the cracked cylinder

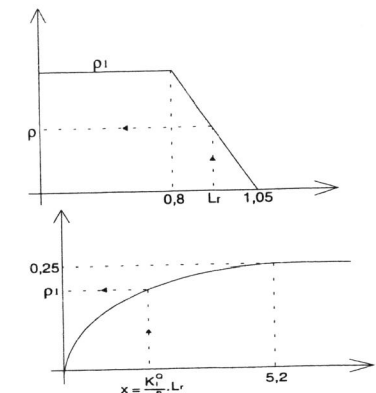


Fig. 3 : Secondary stress factor rho

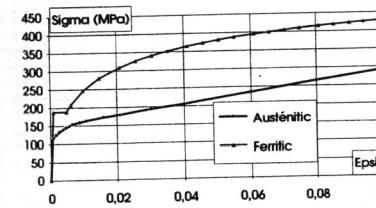


Fig. 2 : Stress-strain curves for austenitic and ferritic steels

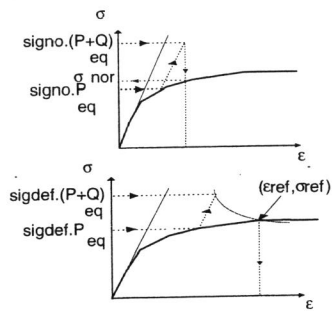


Fig. 4 : k1A16 and Fig. 5 : k2A16

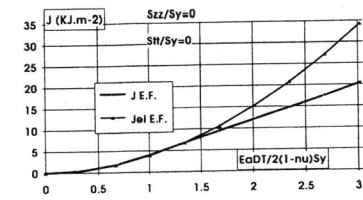


Fig. 6 : Finite Element results for J and Je under thermal loading

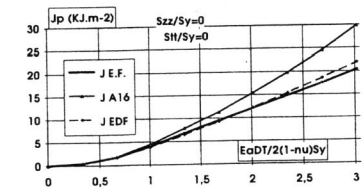


Fig. 7 : Simplified method results for J under thermal loading

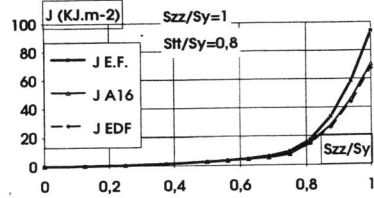


Fig. 8 : Simplified method results for J under mechanical loading

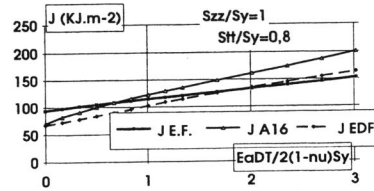


Fig. 9 : Simplified method results for J under combined loading

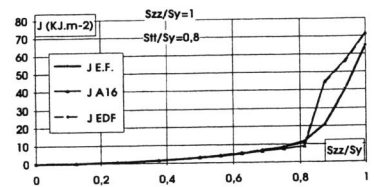


Fig. 10 : Simplified method results for J under mechanical loading on ferritic steel

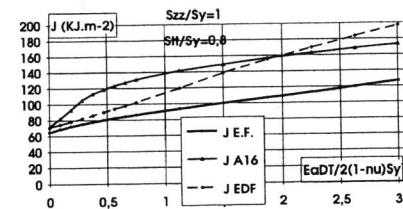


Fig. 11 : Simplified method results for J under combined loading on ferritic steel