SPLASH Test Numerical Modelisations

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1 Introduction

Thermal fatigue induces in-service damage in numerous industrial components, such as parts of nuclear plants, automotive and aeronautical engines and turbines. In this work we are interested in parts subject to thermal shocks which conducts to the formation of crack networks during the lifetime of the component. The aim of this paper is to give an overview of the numerical computational techniques which permit to estimate the elastoviscoplastic behaviour of the parts under a thermal shock and to give a first overall lifetime assessement.

For in-service components, thermo-mechanical loading usually comes from high temperature gradients combined with the stiffness induced by colder or massive parts. An experimental device denoted as SPLASH (see Figure 1) was created within CEA in order to reproduce the temperature gradients due to a thermal shock with the following characteristics :

- a very short rapid temperature change ($\approx 600^o$C / s)
- an important spatial temperature gradient ($\approx 100^o$C / mm)
- a confined plasticity

These experiments permitted to reproduce crack networks with a series of characteristics already obtained in in-service parts. V. Maillot and A. Fissolo [3, 14] conducted a first experimental analysis of the test and obtained important results about crack network morphology and propagation.

The purpose of this work is to analyse numerically the SPLASH experiment in order to propose a method to predict lifetime of structures subject to thermal fatigue loading.

The first section presents the material and the experiments. The next sections presents the thermal analysis, an elastic and a plastic analysis. Finally some fatigue estimations are discussed and conclusions of this work are presented.

2 Material and experimental procedure

The steel studied here is a 304 L type austenitic stainless steel with standard material composition.

In the SPLASH test, temperature gradients are reproduced on two opposite sides of a stiff specimen ($240 \times 30 \times 20$ mm^3), which is continuously heated by an electrical DC current and cyclically submitted to thermal down-shocks performed by water sprayed on opposites faces of the specimen (Figure 1).

The number of cycles to initiation of the crack network is determined by optical microscopic observation of the quenched specimen surfaces at regular time intervals. It is considered that initiation occurs when at least one 50 to $150\mu m$ long crack is observed.

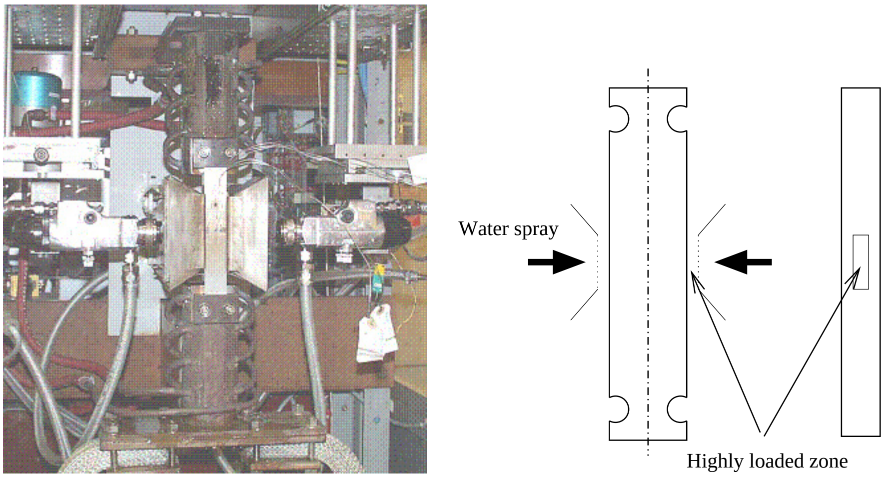

Figure 1: SPLASH specimen

3 Numerical analysis of the experiment

The FEM computations presented in the sequel have been realized using the object-oriented finite element program `Cast3M` [1]. The mesh represented a quarter of SPLASH specimen (see Figure2). It is important to remark that the shortest elements have a length of about $100\mu m$ and are designed such that the temperature and stress gradients are well represented over at least a dozen elements.

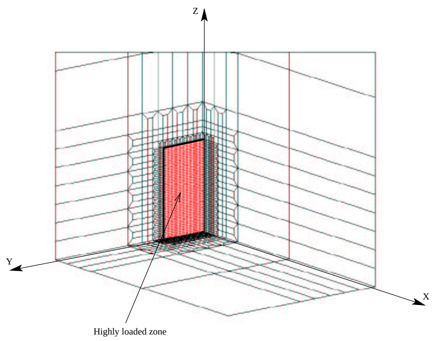

Figure 2: SPLASH specimen mesh

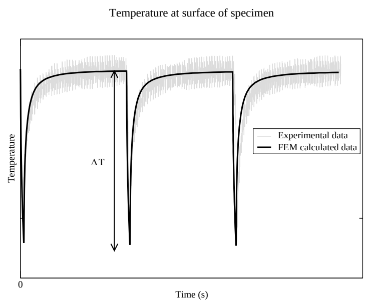

Figure 3: Thermal transient

A first step of the computation is the reproduction of the thermal load. Without getting in all the technical details we shall just state that comparisons have been made between computed and measured values for a series of thermocouples situated on the central axes of the specimen. In Figure 3 we reproduce the comparison of the temperarure variation on one thermocouple.

3.1 Elastic analysis

Due to the large gradients both in time and space, computations easily become cumbersome and in most cases design engineers can only perform elastic analysis. The techniques are later enriched with a elastoplastic interpretation of the result generally based on different variants of the Neuber technique [2].

Therefore we shall start comparing three elastic analysis obtained :

- closed form solution, denoted as the semi-infinite wall (elastic halfspace with confined heating in a vertical cylinder)
- complete FEM calculations
- approximate solution obtained by elastic energy minimization [16] with a special chosen test function

The quenched zone of the SPLASH specimen can be considered as a semi-infinite wall submitted to a thermal shock. The stress difference due to the shock can be defined as :

$$\underline{\underline{\sigma}}^{el} = \frac{E\alpha\Delta T}{1-\nu}(\underline{e_y}\otimes\underline{e_y}+\underline{e_z}\otimes\underline{e_z}) \tag{1}$$

This method assumes an equibiaxial response of specimen and a constant value of stresses along its depth.

The complete FEM calculation shows a biaxial and not equibiaxial response as initially expected (this point will be discussed later) and exhibits an important stress gradient in depth of the specimen.

The proposed simplified solution (much faster than complete FEM calculations) is obtained by minimizing elastic energy.

More precisely, in cylindric coordinates, we assume that elastic stresses tensor is statically admissible, i.e. balances the outer forces, and that its components are polynomial forms, such as :

$$\sigma_{ij}(r,z) = \sum_{k,l} \alpha_{kl} r^k z^l \tag{2}$$

An approximate solution within the set defined by the preeding functions is obtained by minimizing potential elastic energy defined as :

$$U = \frac{1}{2}\int_{\Omega} \underline{\underline{\sigma}} : \underline{\underline{\underline{\underline{\Lambda}}}} : \underline{\underline{\sigma}} dV - \int_{\partial\Omega} \underline{\xi}^d.(\underline{\underline{\sigma}}.\underline{n})dS \tag{3}$$

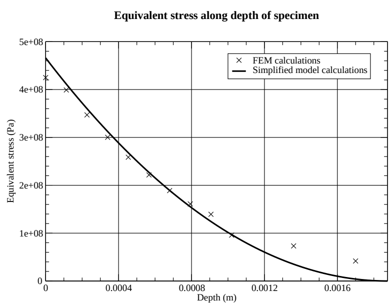

Figure 4: Comparison between FEM and simplified model calculations

In figure 4 we present a comparison between the results obtained from the full FEM computation and the approximate solution obtained by the method explained before. We remark good agrement of stress values at the surface of the specimen and of the gradient along its depth.

For all these methods, strain can be easily obtained using a Hooke's law. Some comparative values of equivalent strains obtained by the three methods are displayed in Table 1.

	Semi-infinite wall	FEM analysis	Simplified analysis
σ_{eq} (MPa)	690	425	466
ϵ_{eq} (%)	0.33	0.20	0.23

Table 1: Results at surface of specimen

3.2 Plastic analysis

Strating from the preceeding elastic analysis, different methods are now presented to perform an elastoplastic analysis:

- K_ν *method* (used in french RCC-MR methodology code)
  Plastic strain can be directly estimated from the strain calculated assuming a pure elastic behaviour by using the K_ν method developped by D. Moulin and R.L. Roche [6] :

$$\Delta\epsilon_{eq}^{t} = K_\nu \Delta\epsilon_{eq}^{el} \tag{4}$$

  where K_ν is a function from $\Delta\epsilon_{eq}^{el}$ and δ which is a modified biaxility ratio.

- *Complete FEM* calculations with an elastoplastic model with linear model kinematic hardening (Figure 5).

- *Complete FEM* calculations with an elastoplastic model with a non-linear model kinematic and isotropic hardening (Figure 5).

- Simplified model based on *Zarka's works* [11]

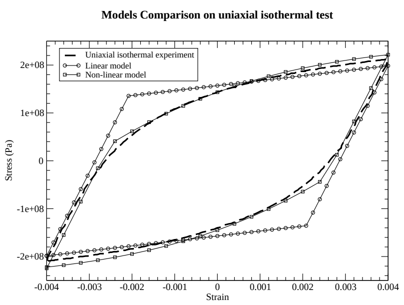

Figure 5: Models comparison on uniaxial isothermal test

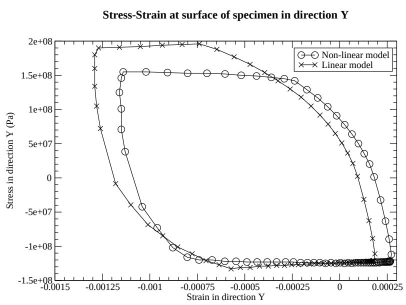

Figure 6: Models comparison on SPLASH stabilized cycle

The result displayed in Figure 6 shows that a series of characteristics of the stabilized cycle, i.e. stress-strain amplitude, cumulated plastic strain per cycle, dissipated energy per cycle, have similar values when the linear and non-linear hardening models are compared. However this is not the case when the load path conducts to a tiny strain, close to a value between 0,001% and 0,002%. This fact can be explained from the uniaxial traction curves of these models (Figure 5) by estimating the gap between linear and non-linear curves.

Besides direct computation, a method to compute the stabilized cycle is Zarka's method. It permits a "quick analysis of inelastic structures" as it computes directly the limit cycle from elastic estimations. It based on Halphen's adaptation theory [10] and Halphen and Son's Generalized Standart Materials formalism [4]. The material is assumed to be with a linear kinematic hardening.

The results of these different methods are displayed in Table 2.

4 Results and discussion on fatigue lifetime prediction

We will compare next the results from numerical computations with experimental observations.

	$K\nu$ method	Linear FEM analysis	Non-linear FEM analysis	Zarka's method
σ_{eq} (MPa)	-	340	300	346
ϵ^p_{eq} (%)	-	0.07	0.10	0.11
ϵ^t_{eq} (%)	0.28	0.20	0.25	0.23

Table 2: Results at surface of specimen

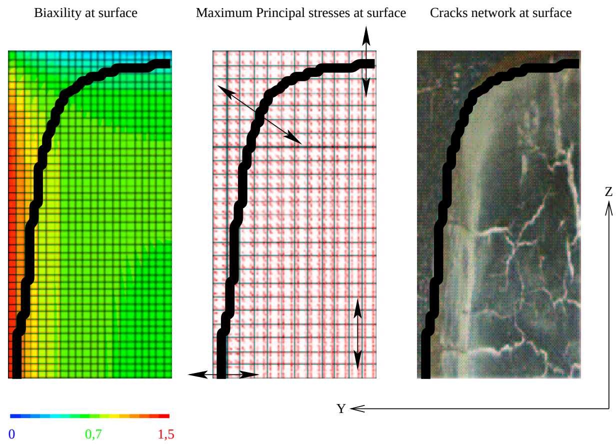

Figure 7: Results from elastic calculations

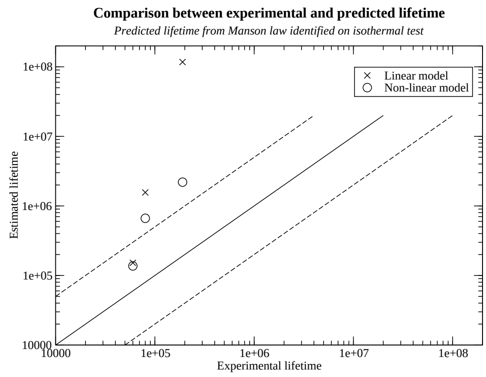

Figure 8: Fatigue lifetime estimation

As a first step let us compare a crack network obtained on the quenched surface with some results of elastic computations (Figure 7). One the one hand one can remark concerning the biaxiality of loading, that inside the quenched zone, the stresses state is biaxial but not equibiaxial :

$$\frac{\sigma_{yy}}{\sigma_{zz}} = 0.7$$

On the other hand stresses at the surface of specimen, indicate a horizontal crack opening near the center of surface loaded, which has been confirmed by experiments.

In order to obtain a fatigue life prediction, we shall use as a first rough approximation the damage indicators based uniaxial mechanical parameters such as plastic strain amplitude (Manson [15]) or maximal stress (Smith-Topper-Watson [12]). The application of the Manson-Coffin law, identified on isothermal uniaxial test, on numerical modelisation results conducts to Figure 8. These results should be commented cautiously : first, to obtain a plastic strain amplitude from plastic computation, we consider an equivalent strain which doesn't take into account the 3D effects of the structure like the state of triaxiality. Second Manson law was identified on an isothermal uniaxial test where failure was denoted a the fracture of specimen and whether in SPLASH we talk about the initiation of a fatigue crack network. Further investigations are actually under consideration in order to better model these facts.

5 Conclusion

The results presented in this work give a comparaison of numerical techniques to predict the behaviour of structures subject to thermal shocks. The methods span a large area of complexity and computational burden, from closed form solutions to complete FEM computations. The results are promising and they show that depending on the desired precision fast results can be obtained by the design engineer. The first lifetime predictions give a rough estimate, however further investigations are however necessary to correlate these results with the complete lifetime preductions.

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