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Development of a test for the analysis of the harmfulness of a 3D thermal fatigue loading in tubes

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Abstract

The incident which has occurred on the Civaux power plant has shown the nocivity of thermal loading and the difficulty to take it into account at design level. The objective of this paper is to study the initiation and the propagation of crack under thermal loading. In this aim the CEA developed a new experiment named FAT3D. The various experiments carried out showed the harmfulness of a thermal loading, which makes it possible to rapidly initiate a network of cracks and to propagate one (or some) cracks through the total thickness of the component under certain conditions. These experimental results associated with a mechanical analysis question the usual criteria of damage based on the variations of the equivalent strain. In addition, the study of the propagation stage shows the capability of classical models to estimate crack growth.

Keywords: Thermal fatigue; Crack propagation; Finite elements; Low cycle fatigue

1. Introduction

The operating conditions of the industrial facilities subject structural materials to a large variety of loading of mechanical and thermal origins which introduce the phenomenon of thermal fatigue. Thermal fatigue originally became a concern in the field of Fast Breeder Reactors (FBR), then in certain components of the pressurized water reactors (PWR) like mixing tees of the Reactor cooling systems.

The design of the current power plants is based on design codes which use simplified rules and fatigue criteria based on uniaxial tensile data. The incident of Civaux in France [1] showed that these rules are not reliable in the case of complex geometries. This incident further demonstrated that the field of thermal fatigue was not completely understood and raised the following questions:

- How to use the uniaxial results to predict thermal fatigue behaviour?
- How cracks propagate under thermal fatigue loading and what crack propagation model should be used?

The role of the Laboratory for Structural Integrity and Standards on this subject is mainly to analyze the initiation and the propagation of cracks under thermal loading. The issue of initiation is already studied on test-tubes subjected to cyclic thermal shocks [2]. The present study focuses on the crack propagation stage.

To understand the incident of Civaux, the laboratory makes numerical studies on the mixing zones [3] and conducts tests in order to validate the results obtained. These tests are thermomechanical experiments named FAT3D. The objective of this article is to present the principle of this test and the first experimental results. After, thermal and mechanical analyses of the test using finite element calculations are presented. Finally, crack initiation and propagation under thermal loading are investigated and compared to classical criteria.

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Nomenclature

h	test-tube thickness	ε_p	plastic strain
E	Young's modulus	ε_e	elastic strain
α	thermal dilatation coefficient	ΔT_1	local thermal gradient
$\Delta\sigma$	stress range	$f(\sigma, X)$	loading surface
$\sigma_{\theta\theta}$	hoop stress	$J_2(\sigma)$	Von Mises criterion
σ_{zz}	axial stress	s	deviatoric part of stress tensor
$\sigma_{\text{equivalent}}$	equivalent stress	p	cumulated plastic strain
$\Delta\varepsilon$	total strain range	K, ΔK	stress intensity factor, stress intensity factor range
$\varepsilon_{\text{equivalent}}$	equivalent strain		
$\varepsilon_{\theta\theta}$	hoop strain	G	energy release rate
ε_{zz}	axial strain	a, c	crack depth, semi-crack length
ε_t	total strain	$\mathrm{d}a/\mathrm{d}N$	crack growth/cycle

2. Principle of test FAT3D

The experiment is performed under 3D thermal loading resulting in a 3D stress–strain loading.

The main objectives of the test were as follows:

- The loading must induce cracks within a reasonable time (to the maximum 3 months).
- To make important crack propagation in such thermal fatigue conditions.

A tube is placed in a furnace (Fig. 1a) which heats the air which is around the test-tube at the temperature T_c and cold water is injected periodically on the internal skin of the tube. The zone cooled by water is parabolic in shape on the internal skin (Fig. 1b). This thermal choc generates many thermal gradients which can be separated in two categories:

- Local gradients which are the temperature difference between the internal skin and the external skin of the tube.
- Global thermal gradients which are a temperature difference between one side of the tube and the other. As for FAT3D's experiments the cooling zone is a parabolic in shape, we have a thermal gradient along the zz axis and another along the $\theta\theta$ axis.

The test-tube is made of 316L austenitic stainless steel tube of 360 mm height, 166 mm in external diameter and 6.7 mm thickness. Various parameters can vary (Fig. 1c):

- duration of the cycle t_c;
- duration of cooling t_f;
- the thickness of the test-tube e;
- the temperature of the furnace T_c.

A cycle can be divided into two parts: a heating stage and a cooling stage. The heating stage is controlled using the parameters t_c and T_c. The cooling stage is controlled by t_f (cold temperature T_f is room temperature).

The thickness of the tube can actually be considered as a preliminary mechanical parameter since it enables to modify the stiffness of the structure. It is a significant parameter that needs to be decided first. In this aim, experiments with different thickness of test-tubes ($e = 6.7$ mm and $e = 17.4$ mm) have been carried out. These tests and associated interpretations showed that with a lower thickness, the loading generated by the global gradients (which develop the 3D effect of the loading) has a higher mechanical influence for lower thicknesses. Indeed the stress generated by the local gradient can be estimated by the equation:

$$\Delta\sigma_1 = \frac{E \cdot \alpha \cdot \Delta T_1}{2 \cdot (1 - \upsilon)} \tag{1}$$

The first mechanical calculations for the highest loaded point show that the structural ratio $\mu = \frac{\Delta\sigma_{\text{total}} - \Delta\sigma_1}{\Delta\sigma_{\text{total}}}$ is higher for the 6.7 mm thickness tube ($\mu = 0.3$) than the 17.4 mm thickness tube ($\mu = 0.1$).

In addition, in order to minimize the period of heating and thus decreased the duration of the cycle, the hot temperature imposed inside the furnace is $T_c = 650$ °C (note that this temperature does not correspond to the maximum temperature of the specimen).

3. Temperature map characterization

To characterize the thermal loading and to develop the numerical model, three thermal types of tests have been carried out:

- A heating test (without cooling) which showed a significant contribution of the radiation of the furnace on the test-tube.
- A cooling test during which water is injected continuously. A 3D quasi-steady thermal state is rapidly achieved in the specimen, and then significant temper-