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Structural behavior during a PTS transient taking into account the WPS effect

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Abstract

The Reactor Pressure Vessel (RPV) is an essential component liable to limit the life duration of PWR's. Its behavior in service is limited in time due to the embrittling effects of irradiation. The structural integrity of the RPV is assessed by conventional fracture mechanical studies, where it is assumed that the failure of a flawed structure occurs when the stress intensity factor at the crack tip reaches the toughness value of the structure material. Toughness curves of materials are obtained from monotonously increasing and isothermal loading. On the other hand, RPV integrity assessment involves loading conditions with coupled cooling, heating, increasing and decreasing load.

The safety analyses made at the European level study, the behavior of defects in the vessel subjected to loading resulting from thermal transients. These analyses usually do not take into account the effect of load history/warm pre-stressing (WPS) of the defects, which is observed in a wide range of experimental studies. The non-consideration of the beneficial effect of this physical phenomenon has two major consequences:

- a poor knowledge of the real margins associated with the transients to which the vessel is subjected,
- an economical penalty due to large under-estimation of the life duration of the vessel.

This paper presents the results of two independent programs.

The first dealing with four WPS tests performed at CEA in France on CT specimens manufactured of ferritic 18MND5 steel undergoing different types of loading during the cooling phase as follow:

- Load Cool Fracture (LCF)
- Loading Maintained CMOD Cooling Fracture (LM2CF)

WPS effect is observed in the first case, while curve in the second case the failure occurs during the crossing of the transition because of the monotonous increase of the force due to constant CMOD (Crack Mouth Opening Displacement).

The second program deals with tests performed at MPA in Germany in collaboration with EDF on CT25 and CT50 specimens using the same material with five types of WPS cycles:

- LCF
- Load Unload Cool Fracture (LUCF)
- Load Transient Fracture (LTF)
- Load Oscillation Cool Fracture (LOCF)
- Load Oscillation Transient Fracture (LOTF)

In all these cases, WPS effect is demonstrated.

For both the programs, numerical analyses were performed at MPA using Weibull [Metall Trans A, 14A (1987) 2277] and Chell [Fourth Int Conf Pressure Vessel Technol, Inst Mech Engng, 1980, Paper C22/80, London, U.K., 117] models to predict the WPS effect, details of which are presented here. © 2001 Published by Elsevier Science Ltd.

Keywords: Reactor pressure vessel; Crack mouth opening displacement; Load cool fracture

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1. Introduction

The warm pre-stress effect means the application of a load to a structure at high temperature prior to a later event or load application at lower temperature. The warm pre-stress effect has been largely reported in the literature [1]. On one hand, authors generally say that the WPS effect elevates the effective fracture toughness of the material, so that crack propagation does not occur when the stress intensity reaches the K_{IC} value of the virgin material identified with an isothermal loading. On the other hand they speak about the conservative principle of the Warm Pre-Stressing effect, which means that after a pre-load of the structure at high temperature, fracture does not occur if the stress intensity factor decreases or holds constant while the crack-tip temperature decreases, even if the virgin material toughness is attained.

Up to now the WPS effect is not considered in the French mechanical assessment of flawed vessels subjected to events such as Loss Of Coolant Accident (LOCA) or Pressurized Thermal Shock (PTS). The integration of this effect into analyses is full of promise since it can prove their present over-pessimism. It is the reason why a certain number of programmes are underway in France similar to those performed in Germany [2–4] to evaluate the beneficial effects.

2. Material data

The material 18MND5 used in this study has been manufactured according to the RCC-M 2126-1988 specifications by Creusot Loire Industrie in 1995 for EDF/DER/MTC. It is a ferritic low alloy steel representative for the material used in French PWR plants. This steel is comparable to SA533 type B Class 2 ferritic steel. Specimens are prepared from a $4000 \times 2000\ mm^2$, $200\ mm^2$ thick rolled plate.

The chemical composition determined by Creusot Loire is shown in Table 1. For information the RCC-M imposed values are also given. The material is well characterized at MPA and also in the framework of a collaborative research programme between CEA, EDF and Framatome. Conventional tests like Charpy, tensile and toughness tests have been performed in the whole transition temperature range. The upper shelf of the transition curve is located at room temperature, the middle of the transition region is located at −50°C, and the lower shelf is below −125°C. Using 16 experimental results obtained with CT-25 specimens (10 at −100°C and 6 at −50°C), the reference temperature $T_0 = -97$°C of the Master Curve approach [5] has been determined. Fig. 1 shows the test results and the tolerance bounds of the Master Curve. All valid K_{JC} values in the range of $-100°C \leq T \leq -50°C$ lay within the tolerance bounds. The experiments are conducted according to the ASTM 1921–97 standard [6]. It can be noted that the Master Curve is slightly optimistic for low temperature (−150°C). Moreover, it is not valid for temperatures above −20°C with respect to the data considered here due to non cleavage (ductile) crack failure.

3. Description of the tests performed at CEA

Two WPS tests have been performed on standard Compact Tension (CT-25) specimens at CEA. These tests were performed in an environmental cooling chamber on a 500 kN servo-hydraulic machine.

3.1. LCF test conditions

After the CT specimen reached a temperature of 0°C at 0 kN, a load of 60 kN was applied. This load value was selected in order to get a stress intensity factor lower than the ductile initiation value at this temperature. This load was maintained at 60 kN during all the cooling phase, i.e. until the temperature of the specimen reached −150°C at a rate of −2°C/min. Then, the load was increased until the rupture of the specimen for a load equal to 68.4 kN. Fig. 2 shows the evolution of load and temperature versus time during the test.

3.2. LM2CF test conditions

As for the LCF test (case 1), the CT specimen first reached a homogeneous temperature of 0°C at 0 kN, then a load of 60 kN was applied. The CMOD reached at $T =$ 0°C was imposed constant during the cooling phase which occurs at the rate of −2°C/min until a homogeneous temperature of −150°C was reached on the CT. Fig. 3 shows the CMOD and the temperature evolution versus time during the test. The fracture of the specimen occurred during the cooling phase at −78°C and for a load equal to 65.4 kN.

3.3. Test results and finite element analysis

The first two WPS tests can be first compared in the

Table 1
Chemical composition of 18 MND 5 in weight percentage

		C	Mn	Si	Ni	Cr	Mo	Cu	S	P	Al	V
1/4 Thickness	Mini	0.175	1.470	0.219	0.652	0.177	0.492	0.084	0.003	0.006	0.017	< 0.005
	Maxi	0.189	1.510	0.225	0.659	0.179	0.507	0.085	0.003	0.006	0.016	< 0.005
RCC-M standard	Mini		1.15	0.10	0.50		0.43					
	Maxi	0.22	1.60	0.30	0.80	0.25	0.57	0.20	0.015	0.02	0.04	0.03