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Thermal fatigue striping damage assessment from simple screening criterion to spectrum loading approach

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ABSTRACT

Thermal fatigue is an important degradation mechanism for the life time assessment of nuclear reactor components. A reliable life-assessment of components is difficult because usually only the nominal temperature differences are known and the thermal surface loadings are not known. This paper outlines a multi-level procedure for assessment of pipe components subjected to thermal fatigue. The different levels are: (a) simple screening criterion, (b) the thermal spectrum replaced by a sinusoidal load (SIN-method) with constant amplitude and frequency and assessment of crack initiation and crack propagation in relation to a critical frequency, and (c) spectrum loading applied to crack initiation and propagation. The different levels are described together with the underlying assumptions. The different levels in the procedure are applied to assess the life of the Civaux case, where a pipe failed due to thermal fatigue. The different levels of the procedure give conservative estimates of the thermal fatigue life but where the conservatism is reduced with the more complex higher level assessments. The influence of important factors such as boundary conditions and primary loads are illustrated. It is also shown that the SIN-method can be used to determine a threshold below which there is no thermal fatigue failure.

1. Introduction

Temperature fluctuations occur in many locations during operation of Light Water Reactors (LWRs), such as the core outlet zone, the lower part of hot pools, free surfaces of the pool, secondary circuit and water/steam interface in steam generators. Fig. 1 illustrates schematically the situation at a mixing tee where cold and hot fluids mix and a turbulent mixing zone occurs at the pipe intersection but the spectrum load is not well known. These temperature fluctuations can lead to thermo-mechanical damage and component failure [1,2]. Typically a large number of surface cracks develop in a fracture network as shown in Fig. 2. Fig. 3 shows measured crack depths from laboratory tests where a heated pipe has been exposed to cold shocks from inside [3]. The key issue in this complex loading, with strong through-wall temperature and strain gradients and with a complex multi-crack distribution, is whether the cracks will arrest at a certain depth or if they will propagate through the thickness. Thermal fatigue is also important for Liquid Metal Fast Rectors (LMFRs) where the temperatures are higher than for LWR and where the properties of the coolant may infer additional problems [1,4,5]. A review of the operational experience is given in [6,7] together with, regulatory framework, countermeasures and current research concerning thermal fatigue problems in nuclear power plants.

Over the last 10 years several R&D programmes have been devoted to developing better understanding of the induced thermal loads and associated damage mechanisms [7,8] showing that a crack growth model was needed to address failures for which several fatigue cracks can initiate at multiple sites and then link together to form a single fatigue crack with a flaw aspect ratio much larger than the standard 6:1 aspect ratio used by ASME Section XI [9] for damage tolerance calculations. Due to the large non-linear gradient stress profiles, cracks will tend to grow in the length direction where the highest surface stresses occur, which leads to defects with very large aspects radios. Much effort continues hence to be devoted to experimental studies and development of models with different levels of complexity [3,10–14].

The thermal fatigue damage depends on the amplitude of the thermal loads, but also strongly on the frequency. At very high frequencies the thermal stresses are confined to the surface and no deep cracks develop. For very low frequencies the temperature gradients and thermal stresses through the wall are small [15,16]. Hence there is an intermediate frequency range for which most fatigue damage is expected. Numerical analyses imply that the fastest crack initiation and propagation occur for frequencies in the range 0.1–1 Hz [4,7,17,18].

In the last decade there has been also an ongoing activity to develop a European procedure for assessment of thermal fatigue [7,19]. This procedure consists of methods with different levels of complexity as shown in Fig. 4. Generally more information is

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Nomenclature

Symbols

a	crack depth
a_i	initial crack depth
a_{cr}	critical crack depth
$2c$	crack length
N	number of cycles
K	stress intensity factor
ΔK	stress intensity factor range
ΔK_{eff}	effective stress intensity factor range
T	temperature
ΔT	temperature range variation
σ	stress
ε	strain
E	Young's modulus
α	thermal expansion coefficient
ν	Poisson ratio
F_u	usage factor
h	heat coefficient transfer
λ	thermal conductivity
ρ	density
c_p	specific heat
Bi	Biot number
C and n	Paris law parameters
r	radial distance across the wall thickness from the inner pipe surface
x_a	normalised crack depth on the wall thickness
l	wall thickness of the cylinder
r_i	inner radius of the cylinder
r_o	outer radius of the cylinder
f	frequency
f^*	normalised frequency
$\Delta\sigma^*$	normalised stress range
p_i	inner pipe pressure
f_k	frequency of peaks of any magnitude of the stress intensity factor
t	time
t_{ref}	reference time
K_r	fatigue strength stress amplitude reduction factor
K_v	plastic strain amplification due to bi-axial thermal stresses
P_f	probability of failure
g	limit state function
D	duration in time
R	$K_{\min}/K_{\max}$ ratio
F_u	usage factor
H	frequency response function
S	power spectrum density function
W	one-side power spectrum density function
τ	order of the moment
ν_p	mean rate maxima
Γ	gamma function
N_{trial}	total number of trial in the MCS
n_{fail}	trials of MCS that satisfy the limit state function
g	limit state function
P_f	probability of failure

Abbreviations

LWR	Light Water Reactor
LMFR	Liquid Metal Fast Reactor
NESC	Network for Evaluation of Structural Components
NULIFE	Nuclear Plant Life Prediction – Network of Excellence
TF	Thermal Fatigue
SIN-method	Sinusoidal method
PSD	Power Spectral Density
FRF	Frequency Response Function
CFD	Computational fluid dynamics

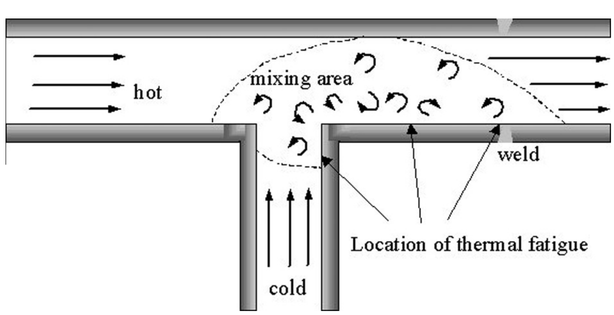

Fig. 1. Schematic representation of the mixing tees scenario.

needed for the higher levels and the analysis is more complex, but the user is rewarded by a more accurate results. The paper will describe in more detail the assumptions and conservatism of the different levels of the procedure. The application of the procedure will also be illustrated by a real case.

2. Methodology

Knowledge of the load is essential in the fatigue evaluation of components. In general the flow characteristic and the thermal loads depend on the temperature of the hot and cold fluids and their physical properties, the component geometry and the flow velocities. The thermal stresses are governed by local temperature fluctuations (amplitude and frequency) close to the wall, and the local heat transfer coefficient.

As mentioned above a multi-level approach has been proposed in the framework of the Network for Evaluation of Structural Components NESCs TF [7]. A general scheme of the levels of analysis addressing thermal fatigue damage in turbulent mixing is shown Fig. 4. The assessment is mainly meant to be elastic. Level 1 is a simple screening criterion for a ΔT, below which there will be no thermal fatigue failure. The more advanced levels have different models for the load whether only crack initiation or crack initiation plus crack propagation is modelled. In Levels 2 and 3, the thermal load is assumed to be perfectly sinusoidal [20–22]. For Level 2 fatigue initiation life for a given ΔT is determined by the frequency that gives the highest fatigue usage factor based on fatigue curves [7], while in Level 3, the fatigue propagation life is determined by the frequency that gives the shortest fatigue crack propagation life using the Paris law approach and defect assessment [23,24]. Levels 4 and 5 use a power spectrum density for the thermal loads instead of a sinusoidal load temperature variation [25] for initiation and crack growth respectively.

The first two levels have been described and analysed by the Network for Evaluation of Structural Components (NESCs) and reported in [7]. Level 3 has been analyses in detail in the European Network of Excellence NULIFE RA4 thermal fatigue pilot project [23] together with parts of Levels 4 and 5. Levels 4 and 5 are more complex and still under development [25].