Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Theoretical and Applied Fracture Mechanics 43 (2005) 77–88
theoretical and applied fracture mechanics
www.elsevier.com/locate/tafmec

Impulse response model of thermal striping for hollow cylindrical geometries

I.S. Jones *

School of Engineering, John Moores University, James Parsons Building, Byrom Street, Liverpool L3 3AF, UK

Available online 25 January 2005

Abstract

The impulse response method is applied to the analysis of the thermally striped internal surface of a hollow cylinder containing a circumferential crack on this surface. Stress intensity factor and strain energy density factor ranges as functions of crack depth for various sinusoidal striping frequencies are calculated. Good agreement is found with both the frequency response and finite element methods. Results for stress intensity factor fluctuations have been applied to the calculation of maximum allowable temperature striping amplitudes. Solutions for striping on the external surface are also presented.

Keywords: Stress intensity factor; Thermal fatigue; Thermoelasticity; Hollow cylinder; Crack

1. Introduction

The phenomenon of thermal striping is the random temperature fluctuation produced by the incomplete mixing of fluid streams at different temperatures. Structures exposed to such temperature fluctuations can suffer thermal fatigue damage. This problem has been discussed in [1–8]. For an engineering component containing a defect and situated in such a flow, the stress intensity factor (SIF), associated with the defect, will fluctuate in response to the imposed surface temperature fluctuations. This will determine the growth behaviour of the defect. For a particular shape of component of a given material under specified external loading, it is often necessary to ascertain the maximum allowable surface temperature fluctuation amplitude before growth of the defect can occur.

Thermal striping fatigue damage has the potential to occur in a number of areas where there is good heat transfer between fluid and component. It can arise in certain liquid metal-cooled fast breeder reactor structures, notably those situated above the core, because of the large temperature differences (up to about 100 °C) which exist between liquid sodium emerging from both the core

* Tel.: +44 151 231 2506; fax: +44 151 207 3460.
E-mail address: i.s.jones@livjm.ac.uk

0167-8442/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tafmec.2004.12.004

and the breeder sub-assemblies. Other areas of potential occurrence include piping systems in pressurised and boiling water reactors where hot and cold flows meet. Thermal stratification can occur in horizontal pipes and high cycle temperature fluctuations can be observed at the interface between the flows. This may result in thermal fatigue cracking on the inside of the pipe at the interface of the fluids [9,10].

Early methods of assessment of thermal fatigue damage caused by thermal striping were carried out using fatigue data obtained from long-life, small, smooth specimens following the approach of the ASME III Boiler and Pressure Vessel High Temperature Code Case [11]. This led to very conservative assessments of allowable thermal striping temperature ranges. It was recognised that engineering components may not be entirely free from defects, particularly in weldments, or that defects may form in service due to thermal shock or creep damage. The 'defect-tolerant' fatigue assessment methods, based on crack growth, have the potential to offer higher allowable thermal striping temperature ranges compared to methods based on smooth specimen fatigue data. These methods are based on linear elastic fracture mechanics. Its applicability to fatigue cracks is discussed in [12]; Fig. 4 in this reference is useful.

The defect-tolerant methods include a frequency response analytical model, TBL, [2,3,6–8] which allows the maximum stress intensity factor fluctuation ΔK for a single defect in the component, to be calculated as a function of defect depth, based on the supplied power spectral density of the temporal surface temperature variation of the component. The flat plate component geometry has been extensively considered [2] with a variety of constraint conditions [3]. The method has been further applied to a cylindrical component geometry containing a circumferential crack [6]. Knowledge of the maximum ΔK as a function of crack depth allows an assessment to be made as to whether any defects will remain static, grow or even arrest at greater depths. Another analytical model, CLOUDBURST [5], is based on the impulse response method. This allows the calculation of the maximum ΔK as a function of crack depth, for the flat plate component geometry. A detailed SIF time history is produced by this method and this allows crack growth times to be calculated, based on a sample of the component surface temperature time history. The third model, STRIPE [1], is based on the finite difference method for the prediction of maximum ΔK values. This allows only certain standard surface temperature time profiles such as sinewaves, ramps, etc. The finite element method has also been used. This may not be suitable for random surface temperature profiles because of the long time intervals involved in analysing high cycle fatigue. It may also be unsuitable for the calculation of ΔK values in defects near junctions in 'multi-structures' (components of different geometries joined together). An asymptotic approach to this latter situation has been investigated recently [13]. An 'evaluation method' for crack propagation has been developed [14] based on a frequency response approach for multiple defects. This has been used to calculate crack growth times based on a Gaussian distribution of surface temperature fluctuations. The methods TBL, CLOUDBURST and STRIPE are based on the weight function approach [15] for the calculation of SIF's. An appropriate weight function for displacement-controlled loading has been developed specifically for thermal striping in [16].

In this paper, the impulse response model will be extended to calculate SIF values in cylindrical geometries. Comparisons will be made with the frequency response model and the finite element method. Finally, the SIF values are used to predict how the strain energy density factors vary with crack depth and frequency of striping.

2. The impulse response model for a hollow cylinder

Consider an isotropic, elastic body occupying a domain G with boundary ∂G containing an edge crack of depth c. Assuming plane strain linear elasticity with generalised coordinates (x_1, x_2), this may be considered as a problem of uncoupled thermoelasticity in which the displacement vector $\mathbf{u} = [u_1(x_1, x_2, t), u_2(x_1, x_2, t)]$ and the temperature $\theta(x_1, x_2, t)$ at time t satisfy the following equations in the absence of body forces: