The Thermal Striping Project

Research in this project is led by Professor Ian Jones. His interest in this topic started when he was employed in full time industrial research at the United Kingdom Atomic Energy Authority in the late 1980s. Fast Breeder Reactors (FBR) were being developed as a solution to reprocessing nuclear waste from more conventional reactor types. Shortly after this time, the UK FBR programme was closed by the UK Government and the prototype reactor at Dounreay (Fig. 1) was de-commissioned. Professor Jones has continued research in this area in academia ever since and is the most highly cited author worldwide on thermal striping (ref. Google Scholar 2012).

Thermal striping is a random temperature fluctuation produced by the incomplete mixing of fluid streams at differing temperatures. Structures exposed to such temperature fluctuations may suffer thermal fatigue damage. For an engineering component containing a defect and situated in such a flow, the stress intensity factor (SIF) and strain energy density factor associated with the defect, will fluctuate in response to the imposed component surface temperature fluctuations. For a component made 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 will occur or, indeed, the component will fail.

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 and the breeder sub-assemblies (fig.2). Other areas of potential occurrence include piping systems in pressurized 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. ‘T junctions’ in piping systems is another area of potential thermal striping fatigue damage (fig. 3).

The theoretical modelling of thermal striping, within this project, was developed on two main approaches; the frequency response method (TBL) [1], and the impulse response method (CLOUDBURST) [4]. When a component is subjected to a thermal load, one objective is to find how the SIF for any defect in the component varies with the length of the defect. Using Fourier analysis, it is usually convenient to examine sinusoidal thermal striping signals (fig. 4). Typical frequencies of the striping signal are shown in fig. 5 (courtesy of UKAEA). Here, a power spectral density plot taken a 0.2-scale air model of the Prototype Fast Reactor Dounreay above core region is shown. A signal sample corresponding to about 30 min real time was taken. The modeling problem may be considered as a problem of uncoupled quasi-static thermoelasticity in order to find the thermally induced stress. The weight function method may then be used to find the sinusoidal variation in the SIF. Some typical results for the amplitude of the SIF for an edge-cracked plate, subjected to a sinusoidal surface temperature load, are shown in fig. 6 for various restraint conditions [2]. The TBL and CLOUDBURST methods show good agreement. Further good comparison of TBL with finite element results are shown in fig. 7 [21] . In general, there are two competing effects. Attenuation of the temperature, and hence stress, with depth would, on its own, lead to a monotonic decrease of SIF with depth. However, there is the geometric effect, through the weight function, of the greater inclination of deeper cracks to grow. These two competing effects can lead to interesting behaviour of the crack such as crack growth followed by crack arrest. High cycle fatigue crack growth may be calculated from the SIF behaviour and an appropriate fatigue crack growth law.

The effect of a spatially incoherent surface temperature load on thermal striping behavior was examined in [3]. The models were extended to other shapes of components such as cylindrical tubes in [5,12].

Some conservatism was removed from the models [6-8] by considering in detail the displacement-controlled nature of thermal loading. Making allowance for crack opening may relieve stress values, resulting in longer component lives for a given level of surface striping. This conservatism is more apparent for edge cracked plates with small aspect ration (fig. 8).

A different form of surface temperature loading was considered in [9]. When backflow occurs in a pipe, a situation may develop with two fluids of differing temperatures flow in opposite directions (fig. 9). Thermal stratification loading occurs when the interface between the two fluids fluctuates. This thermal loading on the inside of the pipe may lead to thermal fatigue. The SIF due to the oscillating fluid boundary loading is found in [9] and shown in fig. 10 as a function of time and crack depth.

There is experimental evidence that thermal striping may result in multiple cracks and even surface 'crazing'. A pattern of multiple edge cracks growth was modelled in [13] using the frequency response approach (fig 11). The effect on the SIF of multiple edge cracks is shown in fig. 12. Not accounting for the presence of multiple cracks may lead to considerable conservatism in structural integrity assessments.

A new asymptotic model was developed in [14] for small defects in a half-space based on the idea of a boundary layer disturbance to the uncracked fields. This model gave good agreement with the earlier models.

In [15] a thermal shock problem was considered. Unlike the analysis of thermal striping, that for a thermal shock requires a dynamic problem to be solved. An asymptotic analysis of the dynamic thermoelasticity problem in an elastic isotropic half-space with a small surface-breaking crack was solved where the surface temperature loading consisted of a series of periodic pulses. The temperature and stress fields together with the SIF were all shown to be composed of an elastic wave term and a diffusion term. Under such a thermal load, the SIF was shown to display a boundary layer (fig. 13) dominated by the diffusion effect. Unlike the static thermal striping problem, this shock problem induces elastic waves which do not attenuate with depth and dominate outside the boundary layer.

In [16-18], the question of thermal striping in materials with microstructure and voids was considered. How is the SIF, and hence the structural integrity of the component, affected by microstructure and voids in the material? In [16], an approximate weight function for an edge crack in the elastic half-plane with multiple voids is developed for finding the SIF. The algorithm developed in [16] is very general and can be applied to edge cracks. Asymptotic formulas for mode I stress intensity factors for an edge crack contained in a half-plane with several voids under a thermal load were considered in [17]. This was also extended to the case of a semi-infinite crack in a perforated elastic plane. The derivation of the formulae relied on the asymptotic approximation of the displacement field, whereas the weight function was taken for the unperturbed geometry.

Using the methodology developed in [16,17], the effect of micro-cracks on the stress intensity factor has been investigated in [18]. Here, we show how the behaviour of the stress intensity factor as a function of crack depth is affected by two micro-cracks of different orientations occurring in a half space (fig. 14). The effect of the presence of these two micro-cracks and their orientation is shown in fig. 15.

The model of mode 1 edge crack propagation within an elastic triangular lattice under thermal striping sinusoidal loading is considered in [19]. Clearly this is no crack tip singularity in the lattice but effective SIFs may be defined appropriately. The stress fields in two lattices, with differing degrees of refinement, are shown in fig. 16. In quasi-static growth, the effective SIF is compared to that in the a continuum, through the homogenisation approximation, in fig 17. and the effect of microstructure may be seen in lowering the SIF values. This may be significant in material choices for structural integrity purposes. At the time of writing, crack propagation in lattices under thermal loading with the inclusion of dynamic effects, are being studied.

Acknowlegements:

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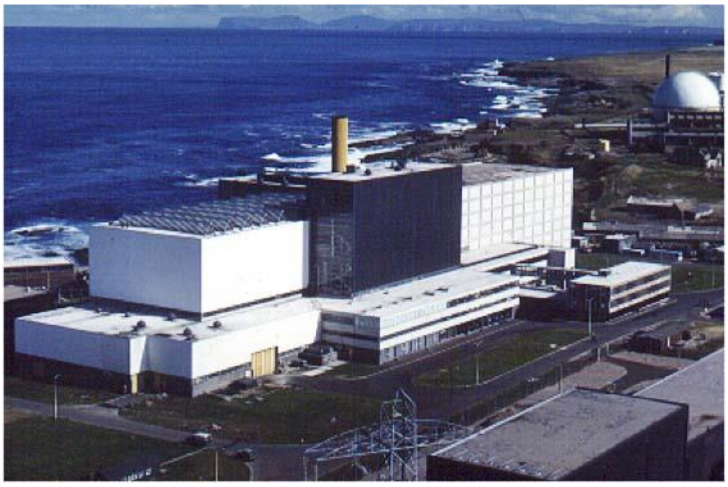


Fig.1 The Prototype Reactor in Dounreay

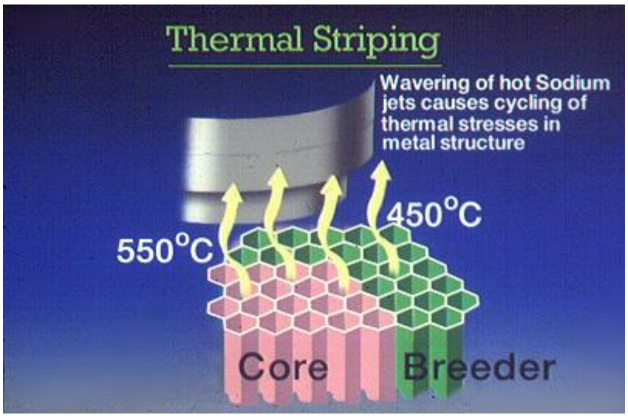


Fig.2 The Thermal Striping phenomenon

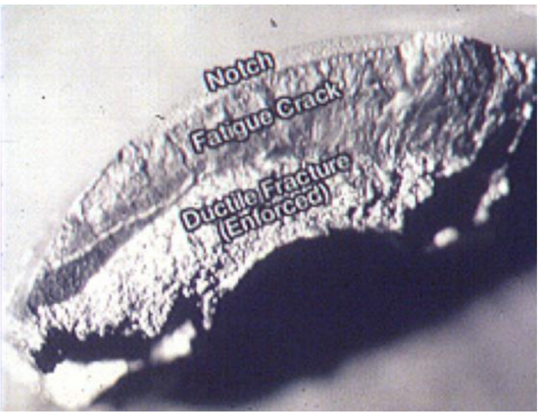


Fig.3 Growth of crack in type 316 stainless steel in liquid sodium caused by thermal fatigue

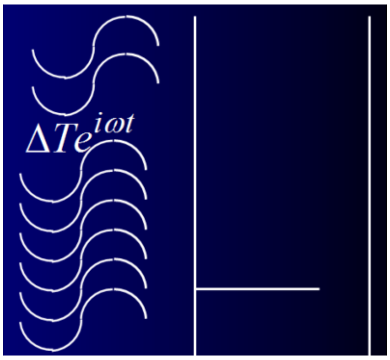


Fig.4 Homogeneous sinusoidal surface striping

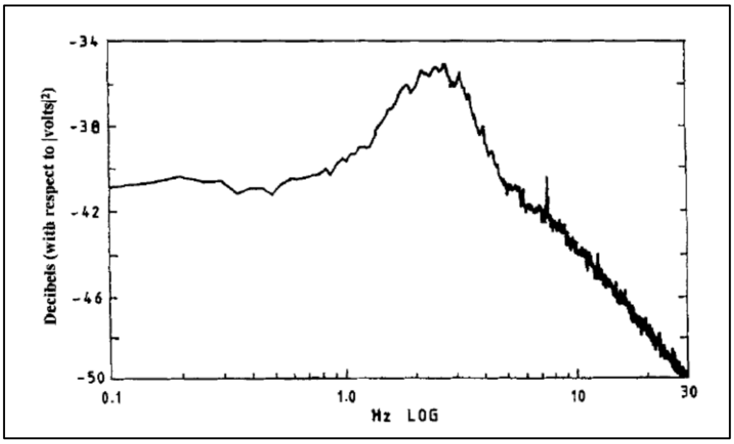


Fig.5 A typical power spectral density for a surface striping signal a 0.2-scale air model of the Prototype Fast Reactor Dounreay above core region. A signal sample corresponding to about 30 min real

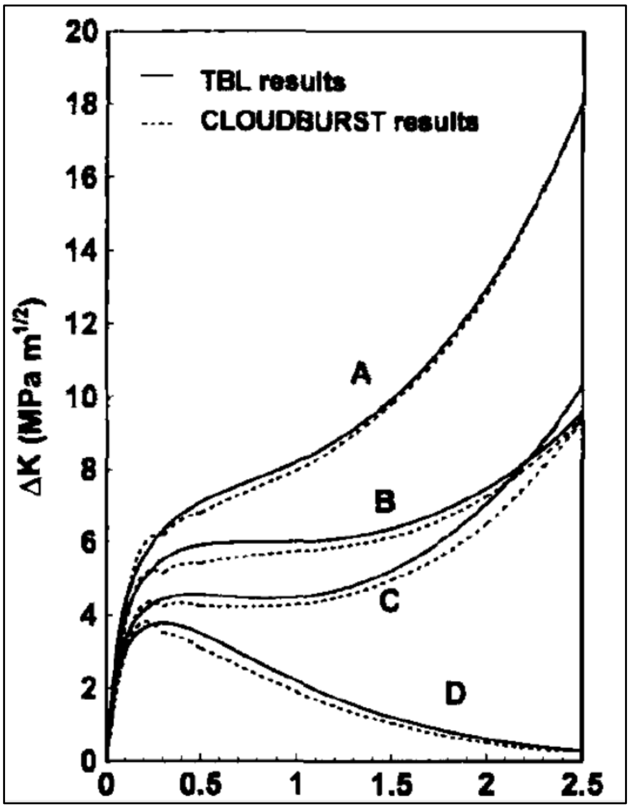


Fig.6 Typical behaviour of the SIF for sinusoidal thermal loading on an edge-cracked plate. A – fully restrained plate. B – bending restraint only. C – membrane restraint only. D – no restraint

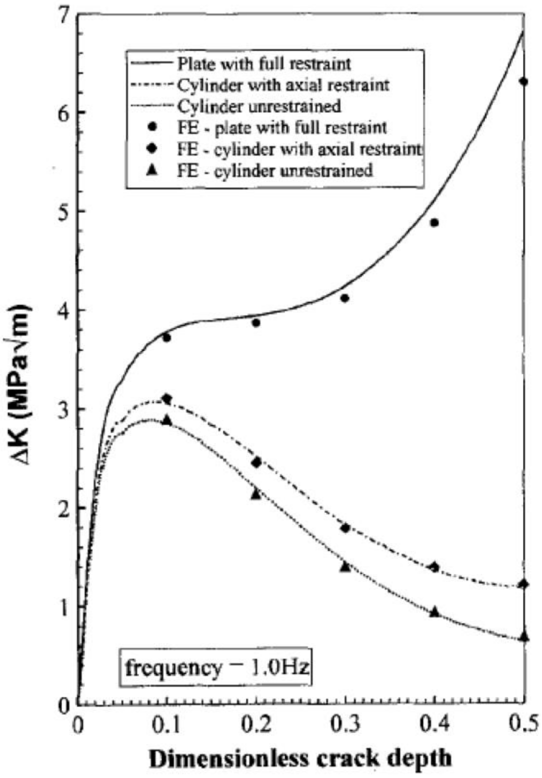


Fig. 7. The variation of the peak to peak stress intensity factor fluctuation with crack depth for the plate and cylinder. Comparison of finite element analysis and TBL results. Striping frequency is 1.0 Hz.

Fig. 7

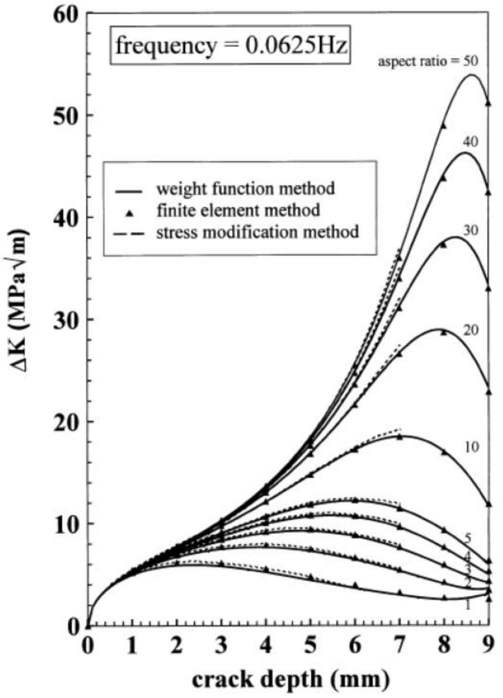


Fig.8 The SIF for the edge cracked plate under sinusoidal thermal striping showing the effect of plate aspect ratio.

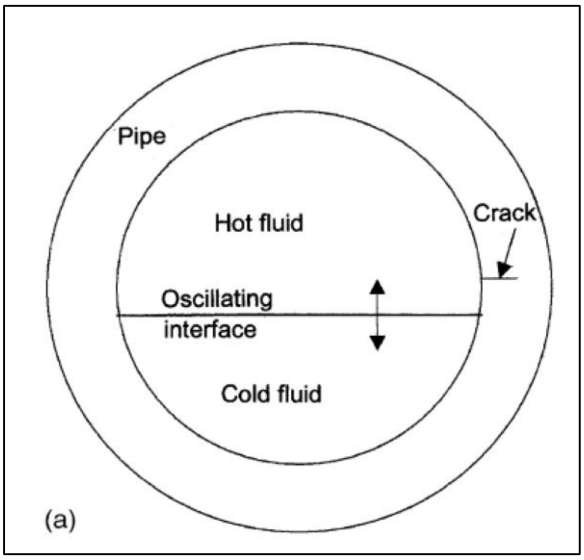


Fig.9 Thermal stratification inside a pipe.

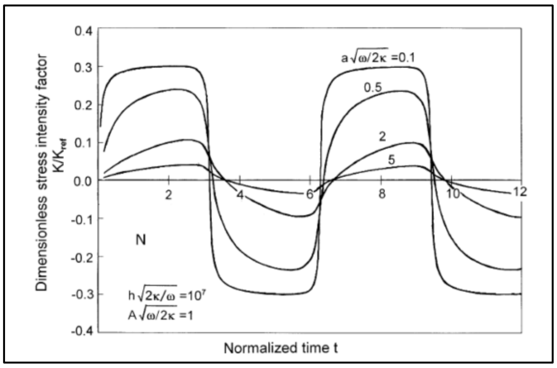


Fig.10 Thermal stratification on the inside wall of a pipe. The SIF for a longitudinal crack as a function of time for different crack depths.

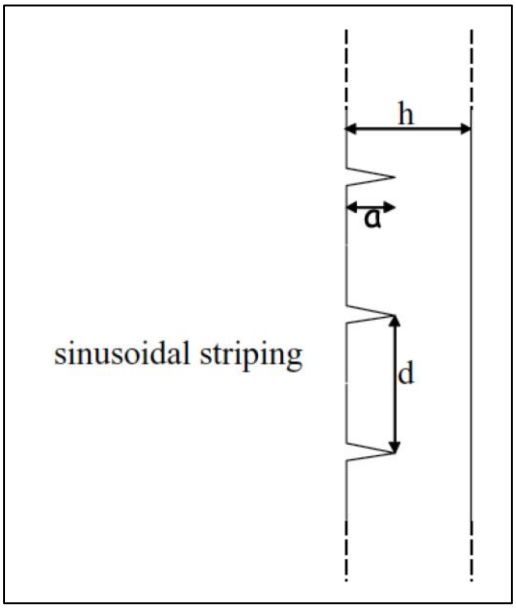


Fig.11. The multiple edge-cracked plate

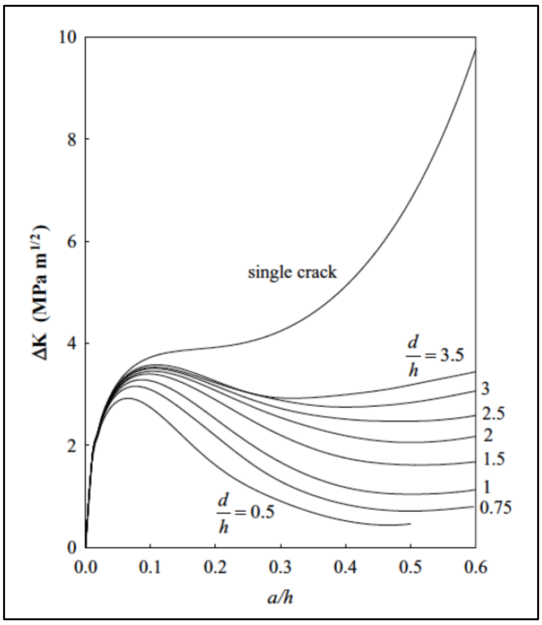


Fig.12. SIF as a function of crack depth for differing crack separations. The plate is fully restrained

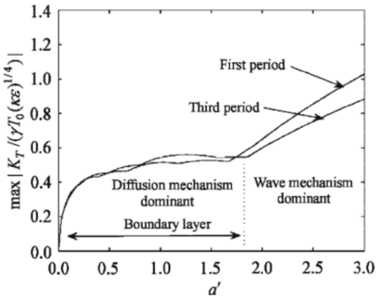


Fig.13. SIF as a function of crack depth for a thermal shock of a half space showing the diffusion dominated boundary layer region and the wave domination region.

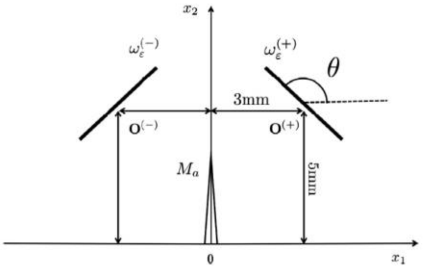


Fig. 2. A half plane containing an edge crack and two micro-cracks $\omega_\varepsilon^{(\pm)}$ with length 3mm and centres $\mathbf{O}^{(\pm)} = (\pm 3\text{mm}, 5\text{mm})^T$. The micro-cracks $\omega_\varepsilon^{(\pm)}$ are at angles of $\pm\theta$ with the x_1-axis.

Fig. 14

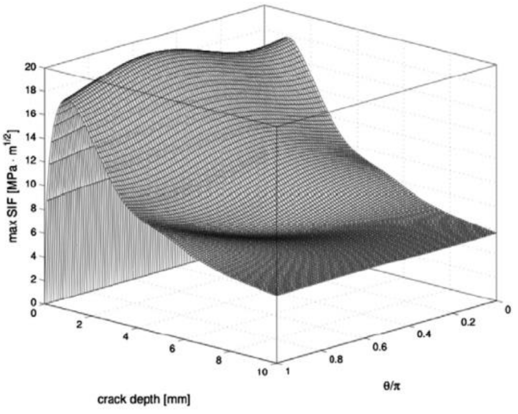
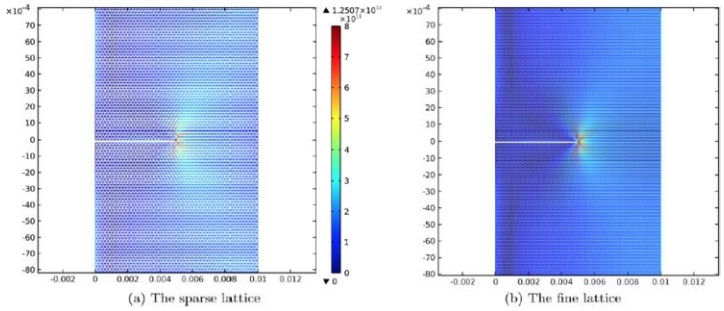


Fig. 3. A surface plot of the amplitude of the SIF $K_{\varepsilon,t}$ against edge crack depth and the normalised angle of orientation of the micro-cracks with length 3 mm and centres $\mathbf{O}^{(\pm)} = (\pm 3\text{mm}, 5\text{mm})^T$, for the case when $\varepsilon = 0.5$.

fig. 15



(a) The sparse lattice (b) The fine lattice

Fig. 2. A comparison of the absolute values of the axial stresses in the sparse and fine lattices.

fig.16

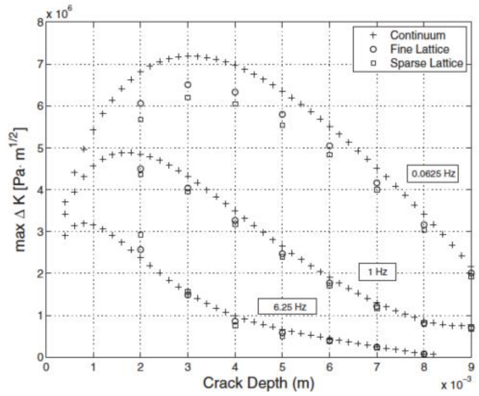


Fig. 4. The maximum ΔK_I for the continuum and the two lattices against crack depth for three characteristic frequencies.

fig. 17