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DESIGN AGAINST FATIGUE FAILURE: CHALLENGES AND SOLUTIONS

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ABSTRACT

This keynote paper will examine why it is much more difficult to design against fatigue than against other modes of failure. Current research will be reviewed, and the ways forward discussed, with reference to recently developed modelling approaches and experimental capability.

Keywords: fatigue, safe life, damage tolerance, short cracks, microstructure.

INTRODUCTION

Components in service can fail by a number of means. Elastic design against yield is now relatively straightforward with the aid of finite element software, and engineering students normally learn about yield before the more complex failure mechanisms. In any case, yield on its own does not necessarily lead to a loss of component functionality, which gives an inbuilt additional margin in many cases. More complex is the case of brittle fracture, but this can normally be dealt with by suitable application of fracture mechanics. Leaving aside the specialist failure modes of creep and corrosion, which occur under specific environmental conditions, this leaves fatigue as a failure mode which must be considered by the engineering designer. It is widely stated that fatigue is the most common cause of failure in service. Nishida (1992) examines 242 failure cases and concludes that 77% of them can be attributed to fatigue. Certainly fatigue is a common failure mode, and even apparently mundane components or systems can give rise to severe consequences as a result of failure. For example, the Killmore East-Kinglake bushfire in 2009 resulted from the failure of a 22kV power distribution line and caused the deaths of 120 people and A$2 billion of property damage (Teague et al, 2010). Similarly, in 2015, fatigue failure of a structural component of the Forth Road Bridge caused the closure of the bridge for 19 days, and considerable disruption, including a 30 mile detour for all traffic. Hence, it is clear that design against fatigue is more challenging than other modes of failure. The paper will examine the reasons for this, and assess the progress towards more effective design tools

THE FATIGUE PROCESS

The earliest attempts to characterise the fatigue process took a total life approach (Wöhler, 1860), where a specimen was subjected to cyclic loading of a constant amplitude, and the life (in terms of number of cycles) recorded. This approach is still used today, and forms the basis of the so-called ‘safe-life’ approach to fatigue assessment (Suresh, 1998). The alternative ‘damage tolerant’ procedure has developed over the past fifty years, based on Paul

Paris's observation that the range of stress intensity factor, ΔK, can be used to characterise the growth rate of a macroscopic crack (Paris and Erdogan, 1963). In either case, assessment entails the comparison of a crack driving force, calculated from the applied loading, with a material response. A number of difficulties and uncertainties arise; as far as the driving force is concerned, we can note the following:

(i) There may be uncertainty in the loading experienced in practice.

(ii) The loading may not correspond directly to that of the experiments used to characterise the material response. For example, laboratory experiments are generally carried out under constant amplitude uniaxial conditions, whereas components may experience multiaxiality and variable amplitude loading.

(iii) For complex loading conditions, it may not even be apparent what a 'cycle' is. Methods such as rainflow counting can help in this respect, but they do not preserve load history information.

In determining the material response, the main difficulty is that of material microstructure. Once a crack is of a particular length, the material may be regarded as macroscopically isotropic, and bulk parameters such as ΔK are useful in relating experimental observations to the practical case. For smaller cracks, however, the microstructure interacts strongly with the crack tip field, leading to the so-called 'Small Crack Problem' highlighted by Miller (1986). Similarly, the local microstructure is the prime influence on crack nucleation. Hence, whether in a specimen test or in a component, it is likely to be the 'worst' microstructure which leads to crack nucleation and subsequent propagation. In effect, the loading is sampling the extreme tail of microstructure within the body. This gives rise to the significant variation in life often observed in plane specimen tests where a large volume (or surface area) is subject to similar stress levels. The same scatter is not observed where the stress is very concentrated (e.g. in notch fatigue or in fretting). Here, the region of high stress is sampling a 'typical' microstructure rather than one from the tail of the distribution.

Recent advances in crystal plasticity modelling techniques and in experimental methods which can examine the interaction of a growing crack with material microstructure offer a potential route forward in characterising the nucleation and small crack regime, and these will be discussed, together with their implications for design.

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