THE USE OF FRACTURE MECHANICS FOR FATIGUE LIFE ASSESSMENT

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SUMMARY

Fatigue failure is a complex physical process, encompassing both crack initiation and crack propagation phases. Using fracture mechanics, fatigue crack growth can be characterised and residual fatigue life evaluated. In the case of a failure, the cause of fracture can be determined forensically. Indeed, fracture mechanics, In conjunction with finite element analysis techniques, has become a very powerful tool for the assessment of the safety and durability of new and legacy based infrastructure projects, the failure of which could have enormous economical and loss of human life consequences.

This paper highlights some of the techniques available and demonstrates their application to a range of fatigue life assessments.

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1: Introduction

Ever since the Industrial Revolution around the 1850s, inventers of machines began to note the phenomenon of premature failure of structures subject to repetitive loading. The German engineer Wohler carried out the first known systematic study of this behaviour on full-scale railway axles. He characterised this behaviour in terms of stress-life (S-N) curves and introduced the concept of fatigue life. Even today, in accordance with the requirements of various national and international codes of practice, fatigue life prediction is carried out under a cumulative fatigue damage assessment methodology using S-N curves that have been generated for various specialist details on the basis of nominal, hot-spot stress or strain based criteria. This assessment methodology provides what is termed as the 'safe-life' of a structure. That is, for the given loading history, the structure will function as designed without failure. For a structure to fail, one or more cracks need to develop and propagate until fracture occurs.

Crack initiation and development is affected by a number of parameters including local geometry, loading history, material properties, fabrication method and environmental conditions. Fatigue failure starts locally with the initiation of micron -sized cracks at the grain boundaries or near inclusions, or at a location which was damaged during the fabrication and handling process. The mechanics and the rate of propagation of these small cracks are yet not fully characterised. Hence the S-N curve approach is used to assess this crack initiation or nucleation phase of the fatigue life. Once the initial crack size becomes discernable, however, the propagation phase of the fatigue life can be determined using a fracture mechanics approach. It is possible that the behaviour of small cracks during the initiation phase, which covers much of the fatigue life, and the growth of larger cracks may one day be fully characterised by a unified fatigue life assessment methodology (Cui et al, 2011). However, until that time the initiation and propagation phases are treated in different ways.

2: Fracture mechanics approach

Starting with the works of early pioneers such as Inglis (1913) and Griffith (1920), research to develop a quantitative relationship between stress and flaw size is still on-going. Griffith (1920) published a paper formulating a fracture theory using energy balance based on the first law of thermodynamics; according to this a flaw becomes unstable causing fracture failure when the strain energy change due to crack growth is larger than the surface energy of the material. Further impetus came from Naval Research Laboratory, USA, from work on the fracture of a number of Liberty Ships during World War II which were fabricated using welded plates. This and the later crash of a Comet aircraft are well known early examples of unexpected fatigue failures. A major breakthrough in prediction of crack growth came in the 1950s (Irwin, 1957) when the principles of linear elastic fracture mechanics (LEFM) became established and a parameter that characterises conditions at the crack tip, the stress intensity factor, was defined. Researchers then turned their attention to crack growth prediction and understanding local behaviour near the crack tip and plasticity ahead of the growing crack. These are still major research areas today.

3: The basic application of fracture mechanics to fatigue

In the simplest form, the application of fracture mechanics to fatigue problems uses LEFM to describe the conditions at the crack tip via stress intensity factors or the equivalent energy release rate. A cyclic loading history is applied and combined with a crack growth law which describes the crack growth rate as function of the stress intensity factor range enables the crack growth to be predicted. The Paris law is the simplest and probably best known form of the crack growth equation. Difficulties then arise in two areas: 1) determining the crack growth law; 2) calculating the stress intensity factors for a general component and loading condition.

Numerical analysis methods have played a significant part in advancing crack growth prediction capabilities since they were first used in the 1970s. The presentation shows examples of application of numerical techniques to several different types of fatigue crack growth problems, some of which are summarised below.

4: Type of applications

Post-failure investigation

Post failure analyses of single cylinder roller bearings used to support the Thelwall viaduct on the M6 motorway in the UK, were carried out to determine the possible cause of premature fracture of nearly 25% of the bearings (Prinja et al, 2009). FEA combined with 3D crack propagation software was used to simulate a small surface crack in the bearing, caused by inter-granular attack during the manufacture (using AISI 420 TQ+T material), and a combination of cyclic rolling and very high contact deck loads. The simulated 3D cracked surfaces, developed due to possible misalignment of bearings, demonstrated a very good match with the actual fractured bearing surfaces and offered an insight into the fracture failure mechanisms comprising modes I, II and III.

Parametric studies

Combing FEA with concepts of fracture mechanics, computational parametric studies of complex piping joints, bonding / debonding of adhesive joints, pre-cracking of specimens, etc., can be carried out. These simulation studies can also help in the setting up and design of laboratory based experiments.

Leak before break

In order to avoid the catastrophic failure of a containment pressure vessel it is important that any cracks that may initiate at highly stressed locations are properly analysed using fracture mechanics techniques. This will ensure that the crack will grow in a controlled manner causing a manageable leak and not sudden rupture or collapse due to ligament plastic failure.

Repairs and life extension studies

Use of composite material patches with strong adhesives have more or less replaced the traditional repair methods of fastening metal plates using bolts and rivets over the cracked area. Using finite element analysis and fracture mechanics software with 3D crack propagation capability, it is possible to simulate the complete adhering and curing process of the patch and its interaction with the plate, and to check the adequacy of the repair and residual fatigue life.

Similarly, life extension of components using various shotpeening techniques can be studied using fracture mechanics and the extended fatigue life evaluated.

Reliability and maintenance

For a durable design of welded structures, it is important that the fatigue life of the structure can be reliably estimated and the crack propagation history leading to failure is predictable. To achieve this, a fracture mechanics model of the connection with an initial crack is calibrated against an appropriate quality S-N curve such that crack growth follows this curve. This allows a proper inspection / maintenance schedule to be set up.

Fail-safe design

For decades, the design and maintenance of structures such as aero engine components used to be based on a low-cycle fatigue life concept (Safe-life). An entire class of components used to be retired from service once the predefined number of cycles was reached. Most of the time, on close examination during inspection, it was noticed that less than one percent of these components actually showed any sign of flaws or damage. This retirement policy was costing US Air Force billions of dollars just to keep the aircraft in flight readiness. Around the mid-1980s, USAF implemented 'retirement for cause', a new policy that requires fracture mechanics based crack propagation analysis , with appropriate safety factors catering for material properties, to determine the actual size of the crack which could cause a fracture failure.

Thermo-mechanical cycles and other complexities

Certain applications include complex effects within the loading cycle. High temperature effects in aerospace engines mean that time dependent crack growth effects can interact with fatigue crack growth. Complex contact conditions in a component can both make the task of calculating a fatigue life more onerous.

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