Fatigue crack initiation in Waspaloy under biaxial loading

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Abstract. This paper reports a series of biaxial fatigue tests carried out under a range of loading conditions with cruciform specimens made of Waspaloy. FE modelling of the specimen was performed to set the test conditions and to predict stress-strain fields and failure location. The effect of strain biaxiality was investigated considering different biaxiality ratios with the same maximum principal stress. Results demonstrate a variation in total life to failure and failure location, confirming the FE predictions. DIC methods were used to spot the cycle in which crack initiation occurred and a microscopic analysis of broken specimens was performed to identify the failure initiation region and fracture surface profile. Finally a number of multiaxial fatigue criteria was investigated and compared using the experimental data.

Introduction

The vast majority of laboratory fatigue tests is performed uniaxially, due to the simplicity of the specimen design and test apparatus. However, many engineering components, such as rotating shafts and turbine disks endure biaxial loading at the surface, where fatigue cracks frequently initiate. Hence there is a clear need to predict fatigue performance under biaxial loading from uniaxial data. The literature is replete with different multiaxial fatigue criteria of varying degrees of popularity [1,2]. However, most of these are validated using tension-torsion experiments, since this is the simplest multiaxial experiment to undertake. However, tension-torsion experiments cannot probe all regions of the π-plane. Thus different techniques are desirable to access more of the principal stress plane. In this work biaxial tests were performed to investigate the biaxiality effect.

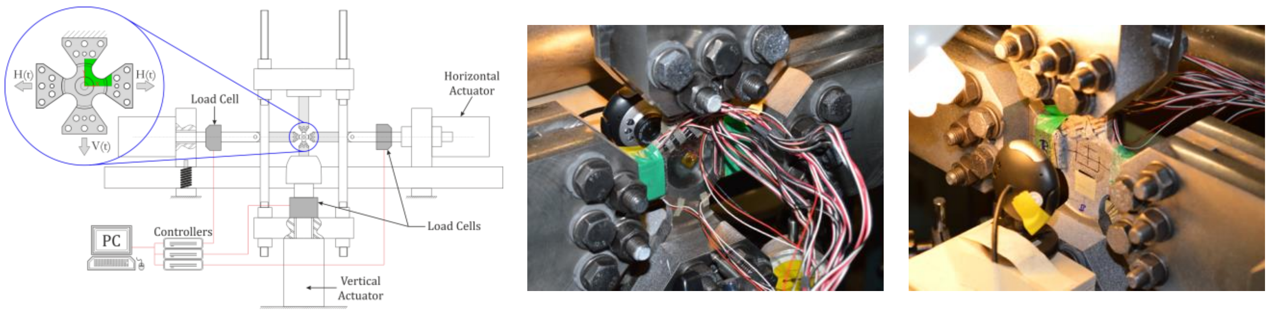
Experimental work

Load controlled fatigue tests were performed using a biaxial rig at the University of Oxford. The testing rig consists of two independent frames carrying hydraulic actuators such that the perpendicular load vectors meet at the centre of the specimen. The vertical load path has a fixed clamp and a large actuator, providing up to 350kN; the horizontal load path has two opposing actuators, providing up to 200kN, mounted at each end of a carriage that is supported on slender rods (Fig 2 (a)).

In total 11 cruciform specimens (Fig 2 (a)) were used to investigate a wide range of biaxiality ratios, with an initial quasi-static cycle to produce limited plastic deformation, followed by fatigue cycling in the elastic regime until failure. Due to the complexity of the tests and physical limitations of the testing machine all tests were carried out at room temperature and at the same load ratio ($R = F_{min}/F_{max} = 0.05$) and low frequency (0.5 Hz).

Strain gauges were connected to the measurement system and used to monitor the tests and any misalignment of the rig (Fig. 2(b)). As an additional measurement, images of the gauge section were obtained during the test to allow use of digital image correlation (DIC) methods to observe the strain field and identify crack occurrence (Fig. 2(c)).

Five different loading cases were establish as to have the same maximum principal stress in each case, and to vary the other in-plane principal stress: Equal biaxial tension (EB); Pure shear (PS), Single Actuator (Uniaxial Load - UL), Uniaxial Stress (US) and Minimum von Mises (Mv). The map of peak stresses in the two principal directions (σ_1 vs σ_2) in Fig. 2(a) graphically represents these test cases.



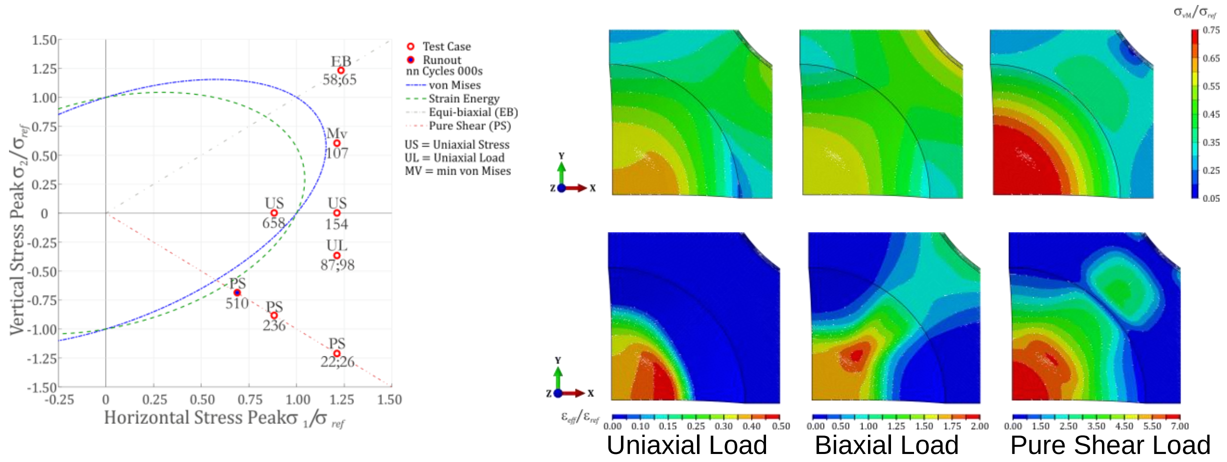
(a) (b) (c)

Figure 1 – (a) Schematic diagram of the biaxial test rig and cruciform specimen with applied loads. (b) Front of the specimen and strain gauge rosettes. (c) Back of the specimen and webcam for DIC methods.

Finite element method

Finite element modelling was employed to analyse the specimen and to estimate the loads required for each test. Actual strain gauge readings were used to confirm whether the required value was achieved during the tests. Simulations of each load combination were initially performed as purely elastic and then as elasto-plastic, considering the maximum von Mises equivalent stress and the maximum effective plastic strain respectively

(Fig. 2(b)). The plastic behaviour was modelled considering a linear hardening law and the material parameters provided by Rolls-Royce plc. Due to the symmetry of the problem only one eighth of the specimen was simulated with appropriate boundary conditions imposed to the symmetry planes (green area in Fig.1 (a).).



(a) (b)

Figure 2 – Map of peak stresses. (b) FE analysis - Elastic at the top and elasto- plastic at the bottom.

Multiaxial fatigue modelling

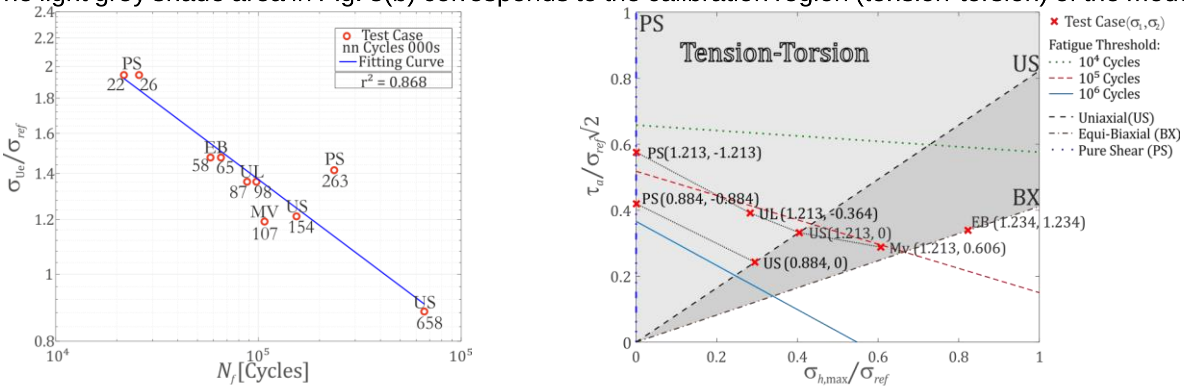
In order to correlate the experimental results and predict fatigue life, several stress based multiaxial fatigue criteria were investigated. Among them, better correlation was obtained with the elastic strain energy equivalent stress and the formulation proposed by Crossland, based on the shear stress amplitude (τ_a) and maximum hydrostatic stress (σ_{hmax}). These formulations are given by Eq.(1) and (2) respectively.

$$\sigma_{Ue} = \sqrt{\sigma_1^2 + \sigma_2^2 - 2\nu\sigma_1\sigma_2}\ , \tag{1}$$

$$\frac{\tau_a}{\sqrt{2}} + \kappa(\sigma_{hmax}) = \lambda\ , \tag{2}$$

where $\sigma_1$and σ_2 represents the principal stress components, ν is Poisson's ratio and κ and λ are material constants determined under fully reversed tension (σ_{-1}) and torsion (τ_{-1}) tests respectively.

Fig. 3 shows the results obtained with these two criteria and the good agreement with the experimental data. The light grey shade area in Fig. 3(b) corresponds to the calibration region (tension-torsion) of the model.



(a) (b)

Figure 3 – Life prediction. (a) Elastic strain energy equivalent stress. (b) Crossland's multiaxial fatigue model.

Conclusion

The results show that the maximum specimen life is experienced under conditions of uniaxial stress, and that the addition of a tensile or compressive stress in the perpendicular direction decreases specimen life. In addition, it is concluded that the elastic strain energy and Crossland's criteria give good predictions.

References

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