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A novel simulation for the design of a low cycle fatigue experimental testing programme

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ABSTRACT

This paper proposes an innovative concept for the design of an experimental testing programme suitable for causing Low Cycle Fatigue crack initiation in a bespoke complex notched specimen. This technique is referred to as the Reversed Plasticity Domain Method and utilises a novel combination of the Linear Matching Method and the Bree Interaction diagram. This is the first time these techniques have been combined in this way for the calculation of the design loads of industrial components. This investigation displays the capabilities of this technique for an industrial application and demonstrates its key advantages for the design of an experimental testing programme for a highly complex test specimen.

1. Introduction

1.1. Research background

Fatigue is a failure mechanism in which gradual damage occurs when a component undergoes cyclic loading. Due to this repeated loading, failure can occur at induced stress levels significantly lower than the ultimate tensile stress and yield stress limits. For this reason, fatigue is potentially very dangerous since even small loads over a large number of cycles can cause catastrophic damage. Structural fatigue is a prominent failure mechanism in engineering components. It is estimated that fatigue is the cause of up to 90% of all mechanical failures in metals [1] and is also the cause of failure for many polymers and ceramics. The fatigue life of a component is expressed as the number of cycles that a component can undergo before critical cracking occurs. Fatigue can be subcategorised into high and low cycle fatigue. High cycle fatigue (HCF) involves low stresses and typically requires more than 10^4 cycles before failure occurs as the deformation at each cycle is primarily elastic. Low cycle fatigue (LCF) occurs when the applied loads are significantly higher and localised plasticity occurs, causing the specimen to fail in less than 10^4 cycles. Since fatigue accounts for so many mechanical failures, the study of fatigue has attracted many researchers for a number of years [2–7] and is still widely investigated today [8–17].

Fatigue is a prominent failure mechanism in many different engineering industries, but arguably two of the most critical are the aerospace and power industries, due to the severe consequences of a structural failure. To this end, extensive finite element and experimental testing is routinely performed in the development of engineering components and also during the life of the component for regular life assessment. The ability to predict a component's fatigue life is vitally important and a number of assessment methods have been developed which are in routine use in industry. These methods are discussed in greater detail in Section 1.4.

In addition to understanding the fatigue life of engineering components, the ability to predict the precise load at which failure will occur is also vitally important in order to ensure their integrity during operational life. For this reason, a thorough understanding of different failure behaviours is crucial both in the component design stage and also during service for condition monitoring purposes. Under cyclic loading, engineering structures can experience a number of different material responses, depending upon the applied load level. These can include purely elastic behaviour, elastic shakedown, reversed plasticity, ratcheting and instantaneous collapse. Understanding the load ranges at which these conditions will occur can aid in the development of engineering components, since damaging behaviour can be avoided through careful design. Ratcheting and instantaneous collapse must be avoided for obvious

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Nomenclature

A	Ramberg Osgood material constant
β	Ramberg Osgood material constant
DCA	direct cyclic analysis
DSCA	direct steady cycle analysis
ε	strain
$\frac{\varepsilon_T}{2}$	total strain range
E	Young's modulus
$\overline{E}$	uni-axial Young's modulus
EPP	elastic perfectly plastic
FE	finite element
GPa	gigapascal
Hz	hertz
θ	temperature load
λ	load multiplier
λ_{LB}	lower bound limit
λ_S	shakedown limit
λ_{UB}	upper bound limit
LMM	linear matching method
MPa	megapascal
N_f	number of cycles to failure
NGV	nozzle guide vane
ρ_{ij}	residual stress
P	static load
$\frac{P}{\sigma_y}$	static load normalised w.r.t yield stress
P_{LIM}	limit load
ΔP	cycled load
$\frac{\Delta P}{\sigma_y}$	cycled load normalised w.r.t yield stress
RO	Ramberg Osgood
RPDM	Reversed Plasticity Domain Method
σ	stress
σ_y	yield stress
$\Delta\sigma$	cyclic stress range
S	surface boundary
Δt	cycle time period
t_n	cyclic time instance
$\dot{u}_i$	displacement rate
V	volume

reasons. However, small amounts of plasticity can be tolerated, provided that it shakes down to fully reversed plasticity or elastic shakedown, since at these loads, continued incremental plasticity and ultimate failure will not occur under repeated loading.

The ability to determine the loads at which each of these structural responses occurs and thus the point at which failure will occur in an engineering component is vitally important. In order to gain a better understanding of this, extensive Finite Element (FE) modelling can be performed and compared to experimental testing. When developing engineering components, it is important to be able to design a test specimen that is sufficiently representative so that during experimental testing, important information about the failure mechanisms of the component can be deduced. This will then aid in the prediction of the failure modes of the engineering structure. For this reason, it is not uncommon to deliberately design a test specimen to fail within a certain life. Fracturing a specimen during experimental testing in a safe, controlled environment provides important information about the failure mechanisms that can occur in the final component, meaning that its design can be adapted if necessary to suit the operating conditions of the engineering structure. This type of testing is prominent in a number of different industries, but is of particular importance in the development of industrial gas turbines, which is the focus of this investigation. This paper concerns the prediction of shakedown and ratcheting failure modes within an experimental test specimen which is representative of gas turbine nozzle guide vanes.

1.2. Linear matching method

The analysis of the steady state response of engineering structures provides invaluable information about the integrity of components when subject to cyclic loading. Few analytical methods exist for this type of investigation and numerical Finite Element modelling can provide much needed information. This steady state response can be calculated with the use of extensive FE modelling in which every cycle is simulated in a separate step of the analysis, this is referred to as a step-by-step analysis. In order to achieve a steady state response, a large number of cycles are required and as a result complete modelling in this way is very computationally expensive and time consuming. This is discussed in greater detail in Section 1.4. Although the increase in computing power in recent years has made this type of analysis more feasible, they cannot always conclusively determine the material response and cannot ascertain the proximity to the limit. Direct cyclic analysis (DCA) methods provide an alternative method of determining the steady state shakedown and ratchet response of structures. A key advantage of these techniques over step-by-step analyses is that full details of the entire load history are not required and instead, only the most dominant loads acting on the structure are required. This leads to significantly reduced computational expense and analysis times, whilst still maintaining a comparable level of accuracy to step-by-step FE methods [18].

The Linear Matching Method [19,20] is such a direct method and it provides a numerical procedure for the calculation of the shakedown and ratchet limits [21]. A number of different direct methods exist for the calculation of shakedown limits, including the Mathematical Programming Method [22], Nonlinear Superposition Method [23] and Repeated Elastic Methods [24]. The shakedown limits can also be determined through iterative methods such as those proposed by Casciaro and Garcea [25,26]. However, the LMM has far greater flexibility and versatility than these other currently existing methods [27]. The LMM has two main unique features over other direct methods. Firstly, the equilibrium and compatibility are satisfied at each stage of the analysis and secondly, it has the capability of performing a detailed ratchet analysis [28–32]. This ratchet procedure also calculates the plastic strain range, making it a viable method for the calculation of the low cycle fatigue life [33]. In addition, the LMM allows the inclusion of temperature dependent material properties and has recently been developed to allow for the inclusion of creep fatigue interaction [34], although this is outside the scope of this current investigation. The Linear Matching Method is operated within the commercial finite element package, ABAQUS [35], through the use of user subroutines. In recent years, the code has also been incorporated into an ABAQUS plugin with an ergonomic graphical user interface (GUI), greatly increasing the ease of use for the user [36–38]. Due to the power of the LMM, it has been part of the R5 research programme for a number of years [28,31] and is routinely used by EDF for the structural analysis of many nuclear power plant components [39,40]. However, despite the major advantages of the LMM, its use is not widespread and is still fairly uncommon outside of the work of EDF.

The LMM process aims to replicate a non-linear, elastic plastic material response through the modification of a series of linear