ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Method to analyse multiple site damage fatigue before and after crack coalescence

G.A. Ruiz-Muñoz *

DONG Energy, Nesa Allé 1, 2820 Gentofte, Denmark
Department of Wind Energy, Technical University of Denmark, 4000 Roskilde, Denmark

ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 9 August 2017
Accepted 8 September 2017
Available online xxxx

Keywords:
Multiple site damage
Finite element
Fracture mechanics
Fatigue
Crack closure

ABSTRACT

The Multiple Site Damage is a phenomenon that appears in e.g. aircraft fuselages and weld geometries. This article introduces a method for solving the Multiple Site Damage fatigue in a 2D specimen. The cases studied are for Linear Elastic Fracture Mechanics situations, isotropic materials and crack growth governed by the Paris Law regime. Already known fracture mechanics concepts are merged together in an innovative algorithm that increases computational efficiency by optimizing the number of Finite Element Analyses necessary for fatigue calculations. A new approach to crack coalescence is presented by using the application limit of Linear Elastic Fracture Mechanics. Comparisons with analytical, experimental and other software results have shown the reliability of this method for several cases. A final explanatory example of a plate with multiple cracks and a hole shows the capabilities of the method proposed.

1. Introduction

Multiple Site Damage (MSD) is a phenomenon that occurs when multiple cracks are located in a structure. MSD can appear from multiple stress concentration locations, but also due to e.g. corrosion pitting [1], poor weld manufacturing techniques as explained in ISO 6520-1:2007 [2] or inherent defects in the material. The aircraft fuselage fatigue cases are examples where multiple cracks are analysed in riveted lap joints [3].

A MSD fatigue analysis helps to determine fatigue growth directions, the number of cycles to failure and predominant cracks. These three concepts are coupled and they are relevant to determine e.g. S-N curves or types of failures in a structure. For applications that require high computational resources, e.g. probabilistic fatigue analysis, a method that is able to automatically design MSD Finite Element (FE) models and efficiently simulate fatigue crack growth is preferred.

The MSD has already been studied using FE models by Jiang et al. [4], where the relation between Stress Intensity Factors (SIF) and crack distributions is presented. The fatigue crack propagation of MSD is shown in recent publications by e.g. Dündar et al. [5], Price et al. [6] and Liu et al. [7]. Dündar et al. use enriched finite elements to compute Stress Intensity Factors for different 2D and 3D geometries. On the other hand, Price et al. propose a MSD fatigue analysis applying dual boundary elements. Liu et al. analyse the crack coalescence through the boundary element method for random crack distributions in 2D studies.

* Address: DONG Energy, Nesa Allé 1, 2820 Gentofte, Denmark.
E-mail addresses: g_a.ruiz@hotmail.com, gusru@dongenergy.dk

https://doi.org/10.1016/j.engfracmech.2017.09.011
0013-7944/© 2017 Published by Elsevier Ltd.

Nomenclature

a, a_{lim}	crack length and crack length limit
b	distance between two parallel cracks
b_i	number of divisions for 2D crack modelling
C_0	Paris Law parameter
d	distance between the crack tip and a boundary
d_{LEFM}	distance of the application Limit of LEFM
d_1, d_2	distance between coordinates in 2D crack modelling
d_{lim}	lower limit distance for the 2D crack modelling
E	Young's modulus
f_{eq}	equivalent crack opening factor
F	external loads
h_1, h_2	global mesh size and mesh size around the crack tip
H	height of a specimen
i, j	integer index
K, K_{max}	Stress Intensity Factor (SIF) and maximum SIF
$K_{eq}, K_{eqmax}, K_{eqop}$	equivalent, maximum Equi. and opening Equi. SIF
K_I, K_{II}	SIF for mode I and mode II
m	Paris Law parameter
n, n_{lim}	number of cycles and number of cycles limit
N_1	number of elements around the crack tip
r	radial distance from a crack tip
R	stress ratio
R_1	mesh parameters
t	thickness of the specimen
W	width of a specimen
x, y	Cartesian axis reference
α	crack opening parameter
$\Delta a_{cum}, \Delta a_{Total}$	cumulative and total crack growth
γ	half crack tip angle
θ_0	deviation from the crack tip orientation
ν	Poisson's ratio
σ	external load
$\sigma_{max}, \sigma_{min}$	maximum and minimum nominal stress
$\sigma_o\ \sigma_{ys}$	flow stress and yield stress
ϕ	crack orientation respect to Cartesian coordinates

The experimental data, however, is scarce. MSD fatigue analysis has already been done by Rahman et al. [8] in the recent years where crack closure was over-imposed to the fatigue numerical model through the Newman's equations.

The coalescence criterion is still a point of discussion. Authors e.g. Rahman et al. [8,3] propose methods such as the Plastic Zone Link-Up (PZL). However, the PZL criterion may reach situations where Linear Elastic Fracture Mechanics (LEFM) is no longer valid and advanced fatigue formulations are required to calculate fatigue life.

The fatigue analysis of multiple cracks requires additional calculations compared to single crack propagation. This publication offers a novel method that optimises the number of Finite Element Analysis (FEA) in a MSD specimen for High Cycle Fatigue (HCF). Cracks are automatically modelled and optimal crack steps are found through the combination of a novel algorithm and convergence analysis.

The study is restricted to 2D specimens, where closure effects are evaluated for MSD mixed mode analysis under plane strain or plane stress conditions. The fatigue analysis only takes into consideration the Linear Elastic Fracture Mechanics (LEFM) approach and assumes that all presented cracks grow according to the Paris Law regime [9]. Crack coalescence is addressed by using the Application Limit of LEFM (ALLEFM). Therefore, the well-known and simple Paris Law formulation is applicable for the entire fatigue analysis. The method presented can operate with complex crack distributions for a large variety of geometries, loads and constraints.

2. Theoretical background

The method explained in this publication combines already known concepts of fatigue, plane strain/stress analysis and boundary analysis. The novelty of this publication is to show how they are merged into a method that is able to perform MSD fatigue analysis before and after crack coalescence, using a low number of FEA for the sake of computational efficiency.