Theoretical and Experimental Modelling of Multiple Site Damage in Plate Components

By

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Abstract

Fracture and fatigue assessment of structures weakened by multiple site damage (MSD), such as two or more interacting cracks, currently represents a challenging problem. The lifetime prediction of structural components with MSD is still largely based on 2D single crack solutions available in various handbooks or derived from the simplified finite element analysis. Such simplifications could often result in non-conservative predictions, overestimating the actual fatigue life of the structural components. Therefore, there is a strong motivation for the development of more advanced modelling approaches, which could incorporate the effects of the interaction between multiple cracks, 3D and other nonlinear phenomena.

The primary objective of this study is to develop analytical and numerical models for the evaluation of the residual strength and fatigue crack growth of two through-the-thickness cracks in a plate of finite thickness subjected to monotonic and cyclic loading. The selected problem represents the simplest type of MSD, however the obtained results can serve as benchmark solutions for modelling and assessment of more complicated practical MSD problems.

The nonlinear interactions between the cracks as well as the 3D effects, such as the effect of the plate thickness, are investigated with the help of the classical strip yield model, plasticity induced crack closure concept and fundamental 3D solution for an edge dislocation in an infinite plate. The computational procedure is

based on the Distributed Dislocation Technique and Gauss-Chebyshev quadrature method, which provide an effective way for obtaining highly accurate solutions to fracture mechanics problems. An experimental study was conducted to evaluate the effect of the plate thickness and crack interaction on the residual strength levels and fatigue crack growth rates of two closely spaced through-the-thickness cracks in aluminium plate specimens. The outcomes of the experimental study were also utilised to validate the theoretical approach and estimate the accuracy of the analytical and numerical predictions.

The major outcomes of the thesis can be formulated as follows:

- An original analytical 3D model for the evaluation of residual strength of two collinear cracks of equal length was developed and compared with the existing 2D models and outcomes of the experimental program conducted by the candidate;
- Analytical and numerical models for the assessment of the fatigue crack growth of two collinear through-the-thickness cracks subjected to a constant amplitude cyclic loading were developed;
- The effects of the nonlinear interactions between two cracks, plate thickness and plasticity induced crack closure on fatigue crack growth rates were identified and analysed using the developed theoretical and experimental techniques;

- Further recommendations for analytical and numerical modelling of MSD were provided.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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List of Publications

Journal publications

1. J. Codrington, A. Kotousov and D. Chang (2012), "Effect of a Variation in Material Properties on the Crack Tip Opening Displacement", Fatigue and Fracture of Engineering Materials and Structures, v 35, pp 943-952.
2. D. Chang and A. Kotousov (2012), "A strip yield model for two collinear cracks", Engineering Fracture Mechanics, v 90, pp 121-128.
3. D. Chang and A. Kotousov (2012), "A strip yield model for two collinear cracks in plates of arbitrary thickness", International Journal of Fracture, v 176, pp 39-47.
4. D. Chang (2013) "Assessment of the interaction between two collinear cracks in plates of arbitrary thickness using a plasticity-induced crack closure model", Fatigue and Fracture of Engineering Materials and Structures, v 36, pp 1113-1122.

Conference publications

1. D. Chang and S. Harding (2010), "A compact solution for the interface corner stress intensity factor of a cylindrical butt joint", 6th Australian Congress on Applied Mechanics, Perth, Australia.

2. A. Kotousov, D. Chang and A. Blazewicz (2010), Scale effects at failure of bi-material joints and structures. 37th Solid Mechanics Conference, Warsaw, Poland.
3. D. Chang and A. Kotousov (2012), "Plasticity-induced crack closure model for two collinear cracks in plates of arbitrary thickness", 7th Australian Congress on Applied Mechanics, Adelaide, Australia.
4. D. Chang and A. Kotousov (2013), "A computational and experimental analysis of interaction between neighbouring collinear cracks in a plate of arbitrary thickness", 8th International Conference on Structural Integrity and Fracture, Melbourne, Australia.

Nomenclatures

2a Crack length

2b Length between outer crack tips of two collinear cracks

2c Length between inner crack tips of two collinear cracks

2d Centre-to-centre distance of cracks

$g(x)$ Crack opening displacement

2h Plate thickness

s, t Transformed coordinates

u_y y-displacement

w Tensile plastic zone size

w' Compressive plastic zone size

x, y Cartesian coordinates

$\Delta b_y(\xi)$ Infinitesimal Burgers vector

$B_y(\xi)$ Edge dislocation density function in y-direction

E Young's modulus

$G_{yy}^{2D}(x, \xi)$ Two-dimensional Cauchy kernel for y-direction

$G_{yy}^{3D}(x, \xi)$ Three-dimensional kernel for y-direction

K_I Stress intensity factor in mode I

ΔK Stress intensity factor range

ΔK_{eff} Effective stress intensity range

$K_0(\cdot)$, $K_1(\cdot)$ Modified Bessel functions of the second kind

Q Contact-free length ratio

R Load ratio ($\sigma_{min}^{\infty}/\sigma_{max}^{\infty}$)

W_j Weight function

β Crack contact zone size

σ_{yy}^{∞} Remotely applied stress in y-direction

$\sigma_{min}^{(n)}$ n^{th} minimum cyclic stress

$\sigma_{max}^{(n)}$ n^{th} maximum cyclic stress

$\sigma_{op}^{(n)}$ n^{th} opening cyclic stress

σ_f Flow stress

σ_Y Yield strength

ε_Y Yield strain

σ_u Ultimate strength

δ_R Residual plastic stretch

$\overline{\phi}(s_j)$ Non-singular function

μ	Shear modulus
κ	Kolosov's constant
ν	Poisson's ratio

Subscripts

i	Inner crack tip
o	Outer crack tip
max	Maximum load
min	Minimum load
op	Crack opening load

Abbreviations

CA	Constant amplitude
CTOD	Crack tip opening displacement
DBEM	Dual boundary element method
DDT	Distributed dislocation technique
DTD	Damage tolerant design
EPFM	Elastic plastic fracture mechanics
FEA	Finite element analysis
LEFM	Linear elastic fracture mechanics
LT	Longitudinal transverse
MSD	Multiple site damage

PICC	Plasticity induced crack closure
RHS	Right-hand-side
VA	Variable amplitude
WFD	Widespread fatigue damage

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