Modelling and analysis of crack turning on aeronautical structures

Doctoral Thesis

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“Quia nolunt dimittere credere pro credere, sed credere per intelligere”

Ramón Llull, s. XIII

Abstract

Developments in airplane structures are aimed at making them lighter, more durable, with higher damage tolerance and simultaneously safer than the existing riveted structures. Integral structures, monolithic or welded, offer weight reduction, costs savings and more corrosion resistance than differential structures (riveted). But, occasionally, they have lower tolerance to the damage. However, by testing these structures with cracks, it has been observed that crack turning may occur. This phenomenon produces an improvement of the damage tolerance inducing crack arresting or deflection.

In order to understand and assess crack turning in aeronautical structures, in this work it has been analysed different Finite Element (*FE*) tools capable to perform crack growth analyses on three dimensional models and, at the same time, with the ability to perform design studies. After assessing different *FE*-analysis tools, the commercial tool StressCheck® has been selected. The *T*-stress extraction facility has been implemented in StressCheck® in cooperation with Engineering Software Research & Development, Inc. The reliability of the tool has been proved to be satisfactory by means of literature and experimental test data. Using this tool and testing Double Cantilever Beam (*DCB*) as well as cruciform specimens under near in-plane opening mode (*Mode I*) loading conditions, different crack turning criteria have been checked.

Based on both testing and simulation results, a more developed criterion is proposed and some hints on the modelling process are recapitulated. The proposed criterion is based on existing criteria related to the *T*-stress and it is implemented with the normalised *T*-stress, T_R. The criterion takes into account the anisotropy of the material and the type of loading, i.e. quasi-static or cyclic loading. Its reliability is successfully proved by testing the *DCB*-specimens. The results of the work provide some confidence for using crack turning for the design process on airplane structures loaded under near *Mode I* conditions.

Keywords: Crack growth simulation; Crack turning; near *Mode I* loading; normalised *T*-stress; anisotropy; airplane structures.

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Nomenclature

α	plane stress/strain constraint factor	[-]
α_0	$= -2k_{II}/k_I$	[-]
α_1	$= K_{Ic}/K_{IIc}$	[-]
α_2	$= K_{Ic}/K_{IIIc}$	[-]
α_e	$= K_I/K_{II}$	[-]
α_{eq}	$= tan^{-1}(K_I/K_{II})$	[-]
α_M	tapered angles for the Mostovoy specimens	[°]
β	$= 2\sqrt{2}\, T / K_I$	[-]
β_m	$= \left(\bar{K}_m^{n_0} - 1\right) / \left(\bar{K}_m^{n_0} + 1\right)$	[-]
δ	crack tip opening displacement	[mm]
δ_{il}	Kroneecker symbol, defined to be *1* when $i = l$ and *0* when $i \neq l$	[-]
Δa	crack growth increment	[mm]
ΔK	*SIF*-amplitude	[MPa*m$^{1/2}$]
ΔK_0	empirical constant for the determination of ΔK_{th}	[MPa*m$^{1/2}$]
ΔK_c	$= K_c\ (1-R)$	[MPa*m$^{1/2}$]
ΔK_i	*SIF* amplitude under *Mode i* with *i = I*, *II* or *III*	[MPa*m$^{1/2}$]
ΔK_{th}	*SIF*-amplitude threshold	[MPa*m$^{1/2}$]
$\Delta K_{I,th}$	*SIF*-amplitude threshold for *Mode I*	[MPa*m$^{1/2}$]
Δx	crack increment on the *x*-axis	[mm]
ε_{ij}	strain field at the crack tip with $i, j = x, y, z$	[%]
Γ	arbitrary contour around the crack tip	
φ	first cylindrical coordinate angle contained in the plane *xy*	[°]
φ_c	turning angle under plane mixed-Mode loading (*Mode I + II*)	[°]
λ	$= \sigma_x/\sigma_y$. Applied stress factor for the *CFS*-specimens	[-]
$\lambda(x)$	*y*-component on the crack path corresponding to the *x*-coordinate for a turned crack	[mm]
μ	shear modulus of elasticity	[MPa]
ν	Poisson's ratio	[-]
ν'	*= 1* for plane stress $= (1-2\nu)^2$ for plane strain	[-]
ρ	process zone	[mm]
σ_0	maximal applied stress (two-stringer specimen)	[MPa]
σ'_I	special principal stress	[MPa]
σ_I, σ_{II}, σ_{III}	Principal stresses	[MPa]
σ^∞	far field stress normal to the crack	[MPa]

σ_c	critical stress, which defines the unstable crack growth	[MPa]
σ_e	Von Mises effective stress	[MPa]
σ_h	hydrostatic stress = $(\sigma_I + \sigma_{II} + \sigma_{III})/3$	[MPa]
σ_{ij}	stress field at the crack tip. $i, j = x, y, z$ for Cartesian coordinates and $i, j = r, \varphi, \psi$ for cylindrical coordinates	[MPa]
$\sigma_{\varphi\varphi}(HRR)$	tangential stress on the *HRR*-field	[MPa]
σ_{max}	maximum applied stress	[MPa]
σ_T	$= T\text{-}\sigma^{\infty}$	[MPa]
τ	$= T/R_{p0.2}$	[-]
τ_c	$= K_{IIc} / \sqrt{2\pi r_c}$	[-]
ω	Twist applied force angle	[º]
ψ	second cylindrical coordinate angle contained in the plane *yz*	[º]
ψ_c	Twist crack turning angle under overlapped loading modes (*Mode I* + *Mode III*)	[º]
ξ	Elliptical function for $\xi = K_c$, R_m and T_R	
A	elongation at fracture	[%]
$\boldsymbol{A_{di}}$	analysis database	
$\boldsymbol{A_k}$	empirical constant on the calculation of the fracture toughness	
B	biaxial parameter	[-]
$\boldsymbol{B_1, B_2}$ $\boldsymbol{B_3, B_4}$	empirical constant for the SINH crack growth rate law	
$\boldsymbol{B_k}$	empirical constant on the calculation of the fracture toughness	
C’	Forman-Newman-deKoning constant	
$\boldsymbol{C_f}$	constant for the Forman crack growth rate law	
$\boldsymbol{C_p}$	constant for the Paris crack growth rate law	
$\boldsymbol{CTOD_c}$	critical *CTOD* which defines the transition between stable and unstable crack growth	[mm]
E	Young’s modulus	[MPa]
$\tilde{E}$	$= E/(1-\nu^2)$ for plane strain = E for plane stress	[MPa]
$\boldsymbol{E_{di}}$	equilibrium database	
F	Force	[N]
G	shear Modulus	[MPa]
$\boldsymbol{G_e}$	energy release rate	
H	local stress triaxiality	[MPa]
J	*J*-integral = $\int_{\Gamma}\left(w\,dy - T_i \frac{\partial u_i}{\partial x}\,ds\right)$	
$\boldsymbol{J_c}$	critical *J*-integral which defines the transition between stable and unstable crack growth	
$\boldsymbol{K_1}$	*SIF* at the turned crack tip defined after Richard	[MPa*m$^{1/2}$]

K_c	under cyclic loading it represents the *SIF* at which the crack propagates at a given rate, for quasi-static loading it is the fracture toughness	[MPa*m$^{1/2}$]
$K_c(\varphi)$	fracture toughness dependent on the anisotropy of the material	[MPa*m$^{1/2}$]
K_i	*SIF* under *Mode i* loading with $i = I$, *II* or *III*	[MPa*m$^{1/2}$]
K_{ic}	fracture toughness under Mode *i* loading with $i = I$, *II* or *III*	[MPa*m$^{1/2}$]
$\overline{K}_m$	$= K_c(\varphi)\big\vert_{\varphi=90^\circ} / K_c(\varphi)\big\vert_{\varphi=0^\circ}$	[-]
K_v	comparative *SIF*	[MPa*m$^{1/2}$]
$K_{vI,II}$	comparative *SIF* under *Mode I* and *Mode II*	[MPa*m$^{1/2}$]
$K_{vI,II,III}$	comparative *SIF* under *Mode I* , *Mode II* and *Mode III*	[MPa*m$^{1/2}$]
L_{rp}	Elastic-plastic behaviour of the ligament	[-]
L_{rv}	plastic degree of the ligament	[-]
M_{cf}	middle point at the crack front	
N	lifetime	[cycles]
N_i	shape function	
$O(l)$	contribution of higher order terms on the stress field at the crack tip	[MPa]
Q	triaxiality parameter	
R	stress ratio	[-]
R_1, R_2 R_3 and R_4	Richard constants for the determination of crack turning angles	[º]
R_c	effect of crack closure under constant amplitude loading	
R_{di}	representational database	
R_k	K-field domain	[mm]
R_m	ultimate yield strength	[MPa]
$R_{p0.2}$	yield strength	[MPa]
S	energy density	
T	uniform non-singular stress, normal to the crack line and dependent on type of loading and specimen geometry	[MPa]
T_i	traction vector	
T_R	normalised *T*-stress (after Pook [16])	[MPa]
T_{xz}, T_{zx}	shear components on the second order term of the William's expansion series for a *3D* crack	[MPa]
T_{zz}	*z*-component of the second order term in the William's expansion series for a *3D* crack = νT	[MPa]
U'	variable field	
U'_i	Variable field on nodal or integral points	
Wt%	weight %	[%]
Z	contraction at fracture	[%]
a	current crack length	[mm]
a_0	initial crack length	[mm]

a_{11}, a_{12}, a_{22} and a_{33}	parameters defining the energy density (*S*)	
c_0	intrinsic crack length = *0.102* mm	[mm]
d	fatigue crack length	[mm]
da/dN	crack growth rate	[mm/cycles]
$erfc$	complementary error factor	
f, f^*	body forces	[N]
$f^{I}_{ij}(\varphi)$, $f^{II}_{ij}(\varphi)$, $f^{III}_{ij}(\varphi)$	functions dependent on crack length and geometry for *Mode I*, *Mode II* and *Mode III* respectively with $i, j = x, y, z$	
f_F	Forman-Newman-deKoning function	
h	specimen half height	[mm]
h_c	opening gap of the notch	[mm]
k_i	*SIF* on the crack path before turning under *Mode i* for $i = I$, *II* or *III*	[MPa*m$^{1/2}$]
l_d	distance between the crack tip and the *CTOD* measure point	[mm]
n	strain hardening exponent	
n_f	exponent constant for the Forman crack growth rate law	
n_Γ	unit vector normal to Γ	
n_o	exponent for orthotropic crack turning calculations	
n_p	exponent constant for the Paris crack growth rate law	
p	Forman-Newman-deKoning exponent	
q	Forman-Newman-deKoning exponent	
r	distance from the crack tip (cylindrical and Cartesian co-ordinates)	[mm]
r_0	explicit distance from the crack tip $= \frac{9}{128\pi}\left(K_I/T\right)^2$	[mm]
r_c	material specific distance from the crack tip	[mm]
r_{cf}	fatigue characteristic length	[mm]
r_{ch}	crack tip parameter	[mm]
r_f	radius of the fuselage	[mm]
r_p	radius of the Irwin plastic zone	[mm]
r-value	anisotropy ratio	[-]
t	thickness	[mm]
t_i	surface traction	[N]
u_i	displacement	[mm]
w	specimen width	[mm]
w_s	strain energy density	
x	cartesian coordinate. Global is defined parallel to the initial notch direction and local in the direction of actual crack propagation	
y	cartesian coordinate. Global is defined perpendicular to the initial notch direction and local perpendicular to the actual crack growth direction	
z	cartesian coordinate in the specimen thickness direction	

Abbreviations

2D	Two Dimensional
2SP	Two Stringer Specimen
3D	Three Dimensional
A/C	Aircraft
AA	Aluminium Alloy
AIMS	Airbus Industries Material Specification (Standard)
BE	Boundary Element
BEM	*BE*-Method
CAD	Computer Aided Design
CATIA	Computer-Graphics Aided Three Dimensional Interactive Applications
CFS	Cruciform Specimen
COD	Crack Opening Displacement
Cr	Chrome
CRC	Corporate Research Centre
CT	Compact Tension (Specimen)
CTOA	Crack Tip Opening Angle
CTOD	Crack Tip Opening Displacement
CTS	Compact Tension Shear (Specimen)
DCB	Double Cantilever Beam
e^-	Electron
E&Sih	Erdogan & Sih (Criterion)
EADS	European Aeronautics Space and Defence (Company)
EPFM	Elastic Plastic Fracture Mechanics
ESRD	Engineering Software Research & Development (Inc.)
Fe	Iron
FE	Finite Element
FEA	*FE*-Analysis
FEM	*FE*-Method
FNK	Forman-Newman-deKonning
HRR	Hutchinson, Rice and Rosengreen (Field)
IINT	Interaction Integral (Method)
LA	Linear Analysis
LEFM	Linear Elastic Fracture Mechanics
MAI	Moscow State Aviation Institute
Mg	Magnesium
MHS	Maximum Hoop Stress (Criterion)
MM	Mixed Mode

MMPDS	Metallic Material Properties Development and Standardisation
Mn	Manganese
Mode I	In-plane opening mode
Mode II	In-plane sliding mode
Mode III	Out-of-plane tearing mode
MPS	Maximal Principal Stress (Criterion)
MSD	Multi Site Damage
MSS	Maximum Shear Stress (Criterion)
MT	Middle Cracked Tension (Specimen)
NASA	National Aeronautics and Space Administration
NLA	Non Linear Analysis
OSM	Object Solid Modeller
R.T.	Room Temperature
SDCB	Twist double cantilever beam
SED	Strain Energy Density
SEM	Scanning Electron Microscope
Si	Silicon
SIF	Stress Intensity Factor
SwRI	Southwest Research Institute
TsAGI	Central Aerodynamic Institute
UPC	Technical University of Catalonia
UTC	University of Technology of Compiegne
VCCI	Virtual Crack Closure Integral (Method)
WEF	Finnie & Saith, Kosai, Kobayashi & Ramulu and Shimamoto et al. (Criterion)
WEFO	*WEF* combined with fracture anisotropy (Criterion)
Zn	Zinc
Zr	Zircon

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