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Leslie Banks-Sills

Interface Fracture and Delaminations in Composite Materials

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Leslie Banks-Sills
School of Mechanical Engineering
Tel Aviv University
Ramat Aviv, Tel Aviv
Israel

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We cannot expect in the immediate future that all women who seek it will achieve full equality of opportunity. But if women are to start moving towards that goal, we must believe in ourselves or no one else will believe in us; we must match our aspirations with the competence, courage and determination to succeed.

Rosalyn Yalow: Medical Physicist, awarded the Nobel prize in 1977

And, for my dear husband, Zvi, my wonderful children, Deborah and Rachel, and my grandchildren.

Preface

After many years of working in the field of fracture mechanics and, in particular, interface fracture and delaminations of composites, I finally was able to put together this brief description of these subjects. I was inspired by former mentors Bernie Budiansky, John Hutchinson, Jim Rice and Lyle Sanders. As some may say, I stood on the shoulders of these giants. Of course, in Israel, I am indebted to Jacob Aboudi for our many conversations over many years at Tel Aviv University. I came to Tel Aviv University as a theoretician and, early on, was requested to build a laboratory. I spent seven years working with Mircea Arcan who aided me in learning experimental methods. There is no greater satisfaction than carrying out experiments which are able to demonstrate various theories. I recommend that to everyone.

Working with many graduate students over the years honed my knowledge of these subjects, as well as others. My first graduate student was Chanan Gabay, an officer in the Israeli Air Force, who knocked on my door one day at Tel Aviv University saying that he had been waiting for me to arrive in Israel in order to work on fracture mechanics. My other students, to whom I am grateful, include: Jacob Bortman, Israel Wander, Daniel Schur, Navah Sela, Izhak Marmur, Aharon Rub, Ami Danieli, Dov Sherman, Yehuda Wolpert, David Loya, Ran Schwartman, Daining Fang, Elimor Makevet, Vadim Leiderman, Dana Ashkenazi, Alla Sherer, Vinodkumar Boniface, Yaacov Schwartz, Avraham Dorogoy, Chaim Ishbir, Orly Dolev, Ron Shachar, Itai Herskovitz, Yuval Freed, Lucy Shemesh, Iddo Kressel, Natalie Konovalov, Dror Decad, Jenny Shklovsky, Yael Buimovitz, Arcady Alperovitch, Liran Rogel, Yael Hikry, Liat Heller, Or Ben David, Maya Gohfeld, Gil Noivirt, Tal Simhi, Guy Shiber, Ido Simon, Elad Farkash, Mor Mega, Tomer Chocron and Hila Ben Gur. Of course, the two engineers who work in my laboratory, Rami Eliasi and Victor Fourman, are always there to help.

I am indebted to an understanding husband who allows me to work all of the time with nary a complaint. My daughters are also remembered for having suffered my absences.

Tel Aviv, Israel — Leslie Banks-Sills
May 2017

Contents

1 Introduction 1
References. 6

Part I Interface Fracture

2 Fundamentals of Interface Fracture Mechanics 9
2.1 Stress and Displacement Field in the Neighborhood of an Interface Crack Tip 10
2.2 Interface Energy Release Rate 12
2.3 Fracture Criterion 13
References. 16

3 Calculation of Stress Intensity Factors – An Interface Crack 19
3.1 Finite Element Method 19
3.2 Displacement Extrapolation Method 22
3.3 M-Integral. 24
3.3.1 Two Dimensions 24
3.3.2 Three Dimensions 28
3.4 Virtual Crack Closure Technique 31
References. 35

4 Testing–Interface Crack Between Two Isotropic Materials 39
References. 43

Part II Delaminations in Composites

5 Mathematical Treatment of Delaminations 47
5.1 The $0°//90°$ Interface. 49
5.2 The $+45°//-45°$ Interface 52
5.3 The $+30°//-60°$ and $-30°//+60°$ Interfaces. 56
5.4 An Interface Between Two Woven Plies 61
5.5 Afterward 62
References. 65

6 Methods of Calculating Stress Intensity Factors–Delaminations 67
6.1 Displacement Extrapolation 67
6.2 *M*-Integral 70
6.3 Virtual Crack Closure Technique 73
References 75

7 Testing–Delamination Between Two Dissimilar Plies 77
7.1 Failure of a Delamination in a Cross-Ply 77
7.2 Beam Type Specimens 82
References 88

Appendix A: Stress and Displacement Functions for the First Term of the Asymptotic Expansion of an Interface Crack Between Two Linear Elastic, Homogeneous and Isotropic Materials 91

Appendix B: Matrices $\mathbf{A_k}$, $\mathbf{B_k}$ and $\mathbf{B_k}^{-1}$ for Different Anisotropic Material Pairs 93

Appendix C: Stress and Displacement Functions for the First Term of the Asymptotic Expansion of an Interface Crack Between Two Anisotropic Materials 111

Index 119

Symbols

a	Half-crack length
a_0	Initial delamination length
A_1	Virtual crack extension area
A_k	Integration area for the M-integral in material k
A_{0k}	Additional integration area for the thermal M-integral in material k
$A_{ij}^{(k)}$	Components of the matrix $\mathbf{A}_k$
$\mathbf{A}_k$	3×3 matrix related to mechanical properties of material k
b	Specimen width
B	Thickness of Brazilian disk specimen
$B_{ij}^{(k)}$	Components of the matrix $\mathbf{B}_k$
$\mathbf{B}_k$	3×3 matrix related to mechanical properties of material k
c	Lever arm
d_i, $\hat{d}_i$	Components of the eigenvectors $\mathbf{d}$ and $\hat{\mathbf{d}}$
$\mathbf{d}$, $\hat{\mathbf{d}}$	3×1 eigenvectors
D_{ij}, $i,j = 1.2.3$	Components of the tensor $\mathbf{D}$
$\mathbf{D}$	Tensor related to Barnett–Lothe tensor $\mathbf{L}_k$
E	Young's modulus
E_k	Young's modulus of material k
E_A, E_T	Axial and transverse Young's moduli
F_{jm}	j-component of nodal point force at node m
g	Ratio of $\mathcal{G}_{II}$ to $\mathcal{G}_I$
G_A, G_T	Axial and transverse shear moduli
$\mathcal{G}$	Griffith's energy or energy release rate
$\mathcal{G}_i$	Interface energy release rate
$\mathcal{G}_1$	Mode 1 energy release rate
$\mathcal{G}_c$	Critical energy release rate
$\mathcal{G}_{ic}$	Critical interface energy release rate
$\mathcal{G}_{ic}^*$	Reduced critical interface energy release rate

$\mathcal{G}_{1c}$	Critical mode 1 energy release rate
$\overline{\mathcal{G}}_{1c}$	Average critical mode 1 energy release rate
$\mathcal{G}_{1c}^{*}$	Reduced critical mode 1 energy release rate
$\mathcal{G}_{I}$	Mode I energy release rate
$\mathcal{G}_{II}$	Mode II energy release rate
$\mathcal{G}_{Ic}$	Mode I critical energy release rate or fracture toughness
$\mathcal{G}_{IR}$	Resistance mode I energy release rate
h, $2h$	Specimen thickness
H, H_1, H_2	Effective Young's moduli
i	$\sqrt{-1}$
$\Im$	Imaginary part of a complex quantity
$\mathcal{I}_I$, $\mathcal{I}_{II}$	Integrals used in VCCT
$\mathcal{I}_I^{(T)}$, $\mathcal{I}_{II}^{(T)}$	Integrals used in VCCT for transversely isotropic material
J	J-integral
$k = 1, 2$	Subscript or superscript denoting upper or lower material
K_I, K_{II}, K_{III}	Modes I, II and III stress intensity factors
K_{Ic}	Plane strain fracture toughness
K	Complex stress intensity factor; also statistical factor
$\hat{K}$	Normalized complex stress intensity factor
K_1, K_2, K_3	Modes 1, 2 and 3 stress intensity factors
K_1^*, K_2^*, K_{III}^*	Local stress intensity factors
$\mathbf{K}$	6×6 rotation matrix
ℓ	Length of finite element
$\ell_1^{(N)}(x_3)$	Length of virtual crack extension in element N
ℓ_j, $j = 2, 3, 4$	Sextic functions
L, l	Longitudinal length measurement
$\hat{L}$	Length scale used in fitting interface fracture test data
$\mathbf{L}_k$	Barnett–Lothe tensor of material k
m, m'	Number of nodal points in an element; also nodal point number
$M^{(1,2)}$	M-integral
n_i, $i = 1, 2, 3$	Components of normal vector
N	Number of samples; also element in which virtual crack extension is carried out
N_i	Shape functions
$p_i^{(k)}$ $i = 1, 2, 3$	Eigenvalues of the compatibility equations
P	Probability of failure
q_1	Normalized virtual crack extension
r, θ	Crack tip polar coordinates
R	Radius of Brazilian disk specimen
$\Re$	Real part of a complex quantity
s	Arc length; also contact zone length in Comninou model; also standard deviation

$s_{\alpha\beta}$ $\alpha, \beta = 1, \ldots, 6$	Components of the compliance matrix
$s'_{\alpha\beta}$ $\alpha, \beta = 1, \ldots, 6$	Reduced compliance components
$\breve{\mathbf{S}}$	3×3 tensor related to oscillatory parameter
$\mathbf{S}_k$	Barnett–Lothe tensor of material k
t	t-statistic
T	Transpose; also total
T_i, $i = 1, 2, 3$	Components of the traction vector
u_i, $i = 1, 2, 3$	Cartesian displacement components
$\mathbf{u}$	Displacement vector
$\mathbf{u}_i$	Nodal point displacement vector
${}_kU_i^{(s)}(\theta)$, $i = 1, 2, 3$	Displacement function for material k, $s = 1, 2, III$
V_k, $k = 1, 2$	Volume in which M-integral is carried out
W	Strain energy density
$W^{(1,2)}$	Interaction strain energy density of solutions (1) and (2)
W_F	Strain energy density for thermal problem
$W_F^{(1,2)}$	Interaction strain energy density for thermal problem
W_{ij}, $i,j = 1, 2, 3$	Components of the tensor $\mathbf{W}$
$\mathbf{W}$	Tensor related to Barnett–Lothe tensors $\mathbf{S}_k$ and $\mathbf{L}_k$
$\mathbf{x}$	Coordinate vector
$\mathbf{x}_i$	Nodal point coordinate vector
z_P, z_γ	Standard variate with probability P and confidence γ
$z_*^{(k)}$	Complex variable given by $x_1 + p_*^{(k)} x_2$
α	Coefficient of thermal expansion
α_A, α_T	Axial and transverse coefficients of thermal expansion
${}_k\alpha_{ij}$ $i,j = 1, 2, 3$	Components of coefficient of thermal expansion for anisotropic material k
β	Dundurs' like parameter
β_A, β_T	Axial and transverse inverse coefficients of thermal expansion
$\tilde{\beta}_k$	Inverse coefficient of thermal expansion for isotropic material k
β_{ij}^k, $i,j = 1, 2, 3$	Inverse coefficient of thermal expansion for anisotropic material k
$\beta_i^{(k)}$, $i = 1, 2, 3$	Related to the eigenvalues $p_i^{(k)}$ for material k
γ	Specific surface energy; also statistical confidence
Γ	J-integral contour
δ_i, $i = 1, 2, 3$	Stress singularities
δ_{ij}	Kronecker delta
Δ, Δ_1	Factors related to the eigenvalues of the compatibility equations
Δu_i, $i = 1, 2, 3$	Crack face displacement jumps
Δa	Virtual crack extension; also crack length increment
ε	Oscillatory parameter

η	Constant related to mechanical properties
ϑ_k	Temperature change in material k
κ	Kosolov's constant
κ_k	Kosolov's constant for material k
λ_k	Lamé constant for material k
Λ	Constant related to mechanical properties
μ	Shear modulus
μ_k	Shear modulus for material k
ν	Poisson's ratio
ν_k	Poisson's ratio for material k
ν_A, ν_T	Axial and transverse Poisson's ratios
ξ, η, ζ	Coordinates in the parent element
ξ_i, η_i, ζ_i	Coordinates of the nodal points in the parent element
Π	Potential energy
σ	Applied tensile stress
σ_{ij}, $i,j = 1,2,3$	Cartesian stress components
${}_k\Sigma_{ij}^{(s)}(\theta)$	Stress function for material k, $s = 1,2,III$, $i,j = 1,2,3$
τ	Applied shear stress
ϕ	Phase angle or mode mixity
ϕ_j	Stress function components
$\boldsymbol{\phi}$	Stress function vector
χ	Angle related to ε and r
ψ	Phase angle or mode mixity
ω	Brazilian disk specimen loading angle
Ω	Constant related to mechanical properties