Materials Science and Engineering R 75 (2014) 1–48

Contents lists available at ScienceDirect

Materials Science and Engineering R

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

Recent developments in brittle and quasi-brittle failure assessment of engineering materials by means of local approaches

F. Berto *, P. Lazzarin

University of Padua, Department of Management and Engineering, Stradella San Nicola 3, 36100 Vicenza, Italy

ARTICLE INFO

Article history:
Available online 10 December 2013

Keywords:
Brittle fracture
Crack
Notch
Local approaches
Strain energy density

ABSTRACT

Brittle failure of components weakened by cracks or sharp and blunt V-notches is a topic of active and continuous research. It is attractive for all researchers who face the problem of fracture of materials under different loading conditions and deals with a large number of applications in different engineering fields, not only with the mechanical one. This topic is significant in all the cases where intrinsic defects of the material or geometrical discontinuities give rise to localized stress concentration which, in brittle materials, may generate a crack leading to catastrophic failure or to a shortening of the assessed structural life. Whereas cracks are viewed as unpleasant entities in most engineering materials, U- and V-notches of different acuities are sometimes deliberately introduced in design and manufacturing of structural components.

Dealing with brittle failure of notched components and summarizing some recent experimental results reported in the literature, the main aim of the present contribution is to present a review of some local approaches applicable near stress raisers both sharp and blunt. The reviewed criteria allowed the present authors to develop a new approach based on the volume strain energy density (SED), which has been recently applied to assess the brittle failure of a large number of materials. The main features of the SED approach are outlined in the paper and its peculiarities and advantages accurately underlined. Some examples of applications are reported, as well. The present review is based on the authors' experience over more than 15 years and the contents of their personal library. It is not a dispassionate literature survey.

Contents

1. Introduction . . . 3
2. Brittle fracture of engineering materials . . . 5
3. Review of some local approaches for the failure assessment of brittle and quasi-brittle materials . . . 7
   3.1. Generalized maximum tangential stress criterion . . . 7
   3.2. Sih's criterion . . . 8
   3.3. Generalized notch stress intensity factors for mode I and mode II loading conditions . . . 9
      3.3.1. Stress distributions due to U- and V-notches . . . 9
      3.3.2. Application of the NSIFs to brittle materials under mode I loading . . . 12
      3.3.3. Notch stress intensity factors for mode II loading . . . 12
   3.4. Neuber's fictitious notch rounding (FNR) approach . . . 12
4. Theoretical background of the volume-based SED approach . . . 15
   4.1. Strain energy density for sharp V-notches under mode I loading . . . 15
   4.2. Strain energy density for sharp V-notches under mixed mode loading . . . 16
   4.3. Blunt V-notches under mode I loading . . . 17
   4.4. Strain energy density for blunt notches under mixed mode loading . . . 19
   4.5. Strain energy density for blunt notches under torsion loading (mode III) . . . 21
   4.6. Some advantages of the SED . . . 21
   4.7. Non-singular higher order terms and three-dimensional problems near notches . . . 23

* Corresponding author.
E-mail address: berto@gest.unipd.it (F. Berto).

0927-796X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.mser.2013.11.001

4.7.1. Higher order terms 23
4.7.2. Three-dimensional problems near notches 23
5. Applications of SED to different materials under mode I–III loadings. 25
5.1. Brittle failure of ceramic materials under mode I loading 26
5.2. Data from polymethyl-methacrylate (PMMA) under different mode loadings 26
5.2.1. Brittle failure data from U- and V-shaped notches in mode I (PMMA at −60 °C) 26
5.2.2. Brittle failure data from U-shaped notches in mixed mode (PMMA at −60 °C). 26
5.2.3. Brittle failure data from U- and V-shaped notches under torsion at room and low temperature (PMMA at −60 °C) 27
5.3. Brittle failure of graphite: recent results 29
5.3.1. Mixed mode failure 31
5.3.2. Torsion loading 32
5.3.3. Compression loading 33
5.3.4. Final synthesis from all graphite specimens 39
6. Application of the SED approach to the fatigue assessment of steel welded joints 39
7. Application of the SED approach to the fatigue assessment of V-notches 41
7.1. Data from notched specimens made of C40 steel (normalized state). 41
7.2. Data from notched specimens made of 39NiCrMo3 steel (hardened and tempered state). 42
7.3. Multiaxial fatigue data from notched specimens made of AISI 416 steel 42
8. Summary and conclusions. 43
References 45

Nomenclature

a	crack depth for cracked specimens and notch depth for notched ones
a_1	real coefficient of the analytical potential functions
a_{ij}	coefficients in the Sih's model
CZM	cohesive zone model
c_w	parameter taking into account the nominal load ratio in the SED evaluation
d	notch depth
E	Young's modulus
E'	generalized Young's modulus.
e_1, e_2, e_3	mode 1, 2 and 3 functions in the SED expression for sharp V-notches
f_{ij}	angular functions in stress field distributions
FNR	fictitious Notch Rounding
F	rupture load
g_{ij}	angular functions in stress field distributions
G	tangential shear modulus
G_F	cohesive fracture energy
H	thickness of the specimen
$H(2\alpha, (R_0/\rho))$	function in the SED expression for blunt notches
H^*	function H in the case of mixed mode loading
h	net width of the specimen
I_1, I_2, I_3	mode 1, 2 and 3 functions in the SED expression for sharp V-notches
I_λ, I_μ, $I_{\lambda\mu}$	integrals in the application of SED to blunt notches
K_t	theoretical stress concentration factor
$K_t(\rho_f)$	stress concentration factor evaluated with fictitious notch rounding
$\bar{K}_t$	effective theoretical stress concentration factor from averaged notch stresses
K_{IC}	material toughness
K_I, K_{II}, K_{III}	mode I, II and III stress intensity factors of a crack
K_1 K_2 K_3	mode 1, 2 and 3 stress intensity factors of a sharp V-notch
$K_{1\rho}$ $K_{2\rho}$ $K_{3\rho}$	mode 1, 2 and 3 notch stress intensity factor of a blunt V-notch
l_{ch}	characteristic length
MTS	maximum tangential stress
q	parameter linked to the V-notch opening angle
r, θ	polar coordinates
r_0	distance between the notch tip and the origin of the polar coordinate system
R_0	radius of the control volume
S	Sih's parameter
SED	strain energy density
s	multiaxiality factor in the FNR approach
T_σ	scatter index in the fatigue curves
W	size of the specimen
$\bar{W}$	averaged strain energy density
W_c	critical strain energy

Greek

2α	opening angle of V-notch
γ	supplemetary angle of α; $\gamma = \pi - \alpha$

Relative deviation

$\Delta\sigma_a$	fatigue strength of the butt ground welded joints
ΔK_{1A}^N	NSIF-based fatigue strength of welded joints
θ_c	angle of the provisional crack propagation
κ	parameter tied to the Poisson's ratio in the Sih's MSED criterion
λ_1, λ_2 λ_3	mode 1, 2 and 3 Williams' eigenvalues for stress distribution at V-notches
λ	biaxiality ratio in fatigue tests (τ_a/σ_a)
μ	exponent in Filippi's stress equations
ν	Poisson's ratio
ρ	Notch radius
ρ^*	microstructural support length
ρ_f	fictitious notch radius
σ_{ij}	ij component of the stress tensor
$\tilde{\sigma}_{ij}$	angular stress functions