

SpringerBriefs in Applied Sciences and Technology

For further volumes:
<http://www.springer.com/series/8884>

Karl-Heinz Schwalbe · Ingo Scheider
Alfred Cornec

Guidelines for Applying Cohesive Models to the Damage Behaviour of Engineering Materials and Structures

Karl-Heinz Schwalbe
ehem. GKSS-Forschungszentrum
Geesthacht
Geesthacht
Germany

Alfred Cornec
Helmholtz-Zentrum Geesthacht
Geesthacht
Germany

Ingo Scheider
Helmholtz-Zentrum Geesthacht
Geesthacht
Germany

ISSN 2191-530X
ISBN 978-3-642-29493-8
DOI 10.1007/978-3-642-29494-5
Springer Heidelberg New York Dordrecht London

ISSN 2191-5318 (electronic)
ISBN 978-3-642-29494-5 (eBook)

Library of Congress Control Number: 2012937865

© The Author(s) 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

1	Scope and Significance	1
1.1	Objective	1
1.2	Traction–Separation Law	2
1.3	Determination of Cohesive Parameters	2
2	Introduction	3
2.1	Motivation for Applying Numerical Damage Models	3
2.1.1	Micromechanics Based Models	4
2.1.2	Phenomenological Models	4
2.2	The Cohesive Model	5
2.2.1	Traction–Separation Law	7
2.2.2	Tangential Separation and Mixed Mode Fracture	10
2.2.3	Cohesive Elements	11
2.2.4	Commercial Solutions for Cohesive Elements	12
2.2.5	Crack Path	12
2.2.6	Further Functionalities	13
	References	14
3	Material Characterisation	17
3.1	Fundamentals and Current Restrictions	17
3.2	Traction–Separation Laws for Global Mode I Fracture	17
3.3	Finite Element Simulations with Cohesive Elements	19
3.3.1	Mesh Generation	19
3.3.2	Stress Calculation	20
3.3.3	Numerical Convergence	21
3.4	Determination of the Cohesive Parameters	21
3.4.1	Direct Identification Procedures	22
3.4.2	Identification Procedure Using Numerical Optimisation	24
	References	30

4 Applications	33
4.1 Damage Free Material	33
4.2 Treatment of Thin-Walled Structures	34
4.3 Simulation of Crack Extension (<i>R</i> -Curves)	36
4.4 Interfaces	37
4.4.1 Welded Joints	37
4.4.2 Delamination	39
4.4.3 Coatings	40
4.5 Prediction of Crack Path	40
4.6 Time Dependent Effects	42
4.6.1 Rate Dependent Formulations	43
4.6.2 Dynamic Fracture	44
4.6.3 Stress Corrosion Cracking	44
4.7 Unloading and Reversed Loading, Fatigue	45
References	46
5 Open Issues	49
5.1 Determination of the Cohesive Energy by a Direct Procedure	49
5.2 Shape of the TSL	51
5.3 Effect of Triaxiality	52
References	57
Appendix A: Worked Examples for the Simulation of Crack Extension	59
Appendix B: Hints for the Treatment of Brittle Materials	87

Summary

This document describes the guidelines for the application of cohesive models to the evolution of damage in materials and structures. The material is characterised by a specific constitutive law, the cohesive law, which is assigned to cohesive elements. These cohesive elements are embedded in a finite element mesh of the structure under consideration.

The cohesive law relates the tractions acting on the cohesive element surface to the material separation and is therefore called traction-separation law (TSL). It can be described by a function, which includes three material parameters:

- The cohesive strength, T_0 ,
- The cohesive energy, Γ_0 , and
- The critical separation, δ_0 ,

which are determined by hybrid experimental/numerical procedures. In addition, the shape of the function must be determined or predefined for a complete description of a cohesive law. If, however, for a given class of materials the shape of the cohesive law is fixed, then only two parameters are needed. In this procedure, the cohesive stress and the cohesive energy are considered the relevant parameters.

The methods described in this procedure can be used for the determination of damage in materials and structures with and without pre-existing flaws, and hence for structural assessment. They are based on experience with metallic materials gained at the Helmholtz-Zentrum Geesthacht (formerly GKSS) as well as taken from the literature. The first part of the suggested procedure describes the material characterisation. In the following section areas of application are compiled. A particularly interesting area of application is the prediction of slow, stable crack extension in thin-walled lightweight structures. Open issues are also briefly described.

In an appendix validation by means of test pieces and application to some structural configurations are given.

Definitions

Traction–Separation Law

A set of equations (also known as cohesive law) describing the relationship between a stress and a separation within the cohesive elements, from zero separation up to loss of coherence.

Ductile Tearing

Crack extension due to micro-void formation and coalescence.

Cohesive Strength

Maximum stress of the traction–separation law.

Cohesive Energy

Area under the curve describing the traction–separation law

Damage

Irreversible process that causes material degradation and finally causes failure. The kind of damage and thus the affected material volume depends on the micro-mechanisms of damage.

Separation

Phenomenological description of material damage and failure by assuming that two initially connected material points separate by some damage process.

Finite Element Method (FEM)

Numerical method based on the principle of virtual work to effectively calculate the material behaviour by dividing a structure into elements with simple displacement formulations.

Cohesive Element

The cohesive element is a special numerical formulation within the framework of finite elements which is able to model the material separation by a cohesive law.

Global Mode I Fracture

Global loading which produces a typical mode I stress field.

Flat Fracture

Fracture surface which evolves normal to the applied loading direction under → *Global Mode I* Fracture conditions.

Slant Fracture

Fracture surface which evolves frequently for thin-walled panels. It turns to 45° (out-of-plane) with respect to the global crack propagation direction.

Normal Separation

Expression used only in the context of cohesive elements. Normal separation is the opening mode of the cohesive elements normal to its interface orientation

Tangential Separation

Like → *Normal separation* only used in the context of cohesive elements. Opening mode of the cohesive elements in the plane of the interface element.

Stable Crack Extension

Crack extension, which, under displacement control, stops when the applied displacement is held constant.

Fracture Resistance

The resistance a material exhibits to stable or unstable crack extension, expressed in terms of K , δ_5 , J or CTOA.

Nomenclature

Dimensions

- a Crack length
- a_0 Initial crack length prior to ductile crack extension
- t Specimen thickness
- W Specimen width

Tensile Properties

- E Young's modulus
- ν Poisson's ratio
- $R_{p0.2}$ Yield strength equivalent to 0.2 % proof stress
- R_m Tensile strength
- σ_Y Yield strength, general

Forces, Stresses and Displacements

- F Applied force
- h Stress triaxiality, calculated by σ_m/σ_{eff}
- v_{LL} Load-line displacement
- σ Normal stress
- σ_{eff} Effective stress
- σ_m Mean stress, also called hydrostatic stress, $\sigma_m = \sigma_{ii}/3$

Fracture Parameters and Related Quantities

- Δa Crack extension
- J Fracture resistance in terms of the experimental equivalent of the J -integral
- J_i Value of J at initiation of ductile tearing
- Ψ Crack tip opening angle

δ_5 Crack opening displacement measured at the surface of a specimen or structural component at either side of the original crack tip over an initial gauge length of 5 mm

Cohesive Parameters

T Cohesive stress
 T_0 Cohesive strength
 Γ_0 Cohesive energy
 δ Separation
 δ_0 Critical separation
 δ_n Separation normal to the fracture surface
 δ_t Separation tangential to the fracture surface

The SI Units to be used in this Procedure are:

F Force, kN
 σ, T Stress, MPa
 δ_5 Displacement, mm
 Δa Crack extension, mm
 J Experimental equivalent of J -integral, MPa m

Acronyms

CMOD Crack mouth opening displacement
CTOA Crack tip opening angle
CTOD Crack tip opening displacement
TSL Traction—separation law
FEM Finite Element Method