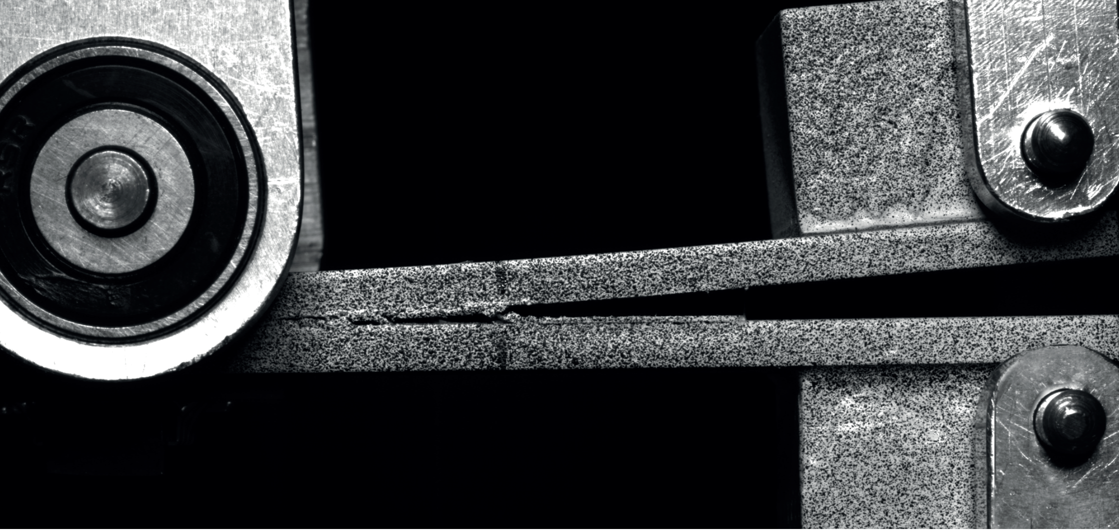

Aachener Berichte aus dem Leichtbau

Fracture Characterisation of Adhesively Bonded Joints under Mixed-mode Loading

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Institut für Strukturmechanik und Leichtbau

RWTH AACHEN UNIVERSITY

Fracture Characterisation of Adhesively Bonded Joints under Mixed-mode Loading

Charakterisierung des Bruchverhaltens von Klebungen unter Mischbeanspruchung

Von der Fakultät für Maschinenwesen der
Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines
Doktors der Ingenieurswissenschaften
genehmigte Dissertation

vorgelegt von

Mohammad Zamaan Sadeghi

Berichter: Univ.-Prof. Dr.-Ing. Kai-Uwe Schröder
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Aachen, September 2020
Mohammad Zamaan Sadeghi

Abstract

Adhesively bonded joints have been increasingly used in structural applications over the last decades, and are observed as alternatives to traditional methods of mechanically fastened and welded joints. Amongst various industries, aerospace and automotive have contributed immensely toward development of adhesives with the increase in the use of hybrid structures in the lightweight design. Adhesively bonded joints are frequently subjected to either static or fatigue mixed-mode loadings. Hence, attempting a conservative design to compensate for the negative effects of such loadings should be considered by the designers. Nevertheless, the lack of reliable material modelling as well as inherent uncertainties existing in such joints result to over-design of such components. Therefore, improvement in the structural integrity of components using such joints while they are in service is still a matter of discussion. Although there have been many works in fracture characterisation of adhesives under pure mode I and II, their response under mixed-mode loadings has received much less attention and many points still need to be investigated.

This work presents a framework for determining fracture properties of a ductile adhesive under mixed-mode loading by using mixed-mode bending (MMB) tests. To this end, three different investigations (experimental, analytical and Finite Element (FE) method) were carried out in the present work. For determining the strain energy release rate (SERR) of the adhesives under MMB tests, a closed form relation was offered based on the equivalent flexural modulus and equivalent crack length which is capable of capturing the nonlinear effects forming in the crack tip. This method is independent of monitoring the crack length. In addition, a newly proposed J-integral method was implemented for determination of SERR of the adhesive used in the present work. This method is not dependant on the elastic properties of the adhesive, adherents, crack measurements, compliance of the system, etc. which can hugely improve the accuracy of the measured fracture energies. In addition, the effect of adhesive layer thickness on the determined critical SERR (CSERR) was investigated. It was observed that CSERR unlike pure mode I which is highly dependent on adhesive layer thickness, in mixed-mode loading is not very much dependent on the adhesive layer thickness.

Different FE models were also developed in this work for different purposes: determination of CSERR (using J-integral contour), benchmarking for prediction of failure loads in bonded joints under mixed-mode loading, validation of the analytical approaches used in the present work.

Kurzfassung

Klebeverbindungen werden in den letzten Jahrzehnten zunehmend in strukturellen Anwendungen eingesetzt und dienen als Alternative zu den traditionellen Verbindungstechniken wie Nieten oder Schweißen. Der zunehmende Einsatz von Hybridstrukturen im Kontext des Leichtbaus insbesondere im Bereich der Luft- und Raumfahrt und der Automobilindustrie haben die Entwicklung der Klebetechnologie maßgeblich befördert. Klebeverbindungen werden in den unterschiedlichen Anwendungen sowohl statisch als auch dynamisch belastet. Eine zuverlässige und konservative Auslegung der klebeverbindung erfordert daher geeignete Methoden für beide Belastungsfälle. Aktuell fehlen jedoch allgemeingültige Materialmodelle und Methoden die eine zuverlässige Auslegung ermöglichen wodurch Klebeverbindung häufig überdimensioniert ausgelegt werden. Folglich ist die Verbesserung der strukturellen Integrität von Komponenten, die solche Verbindungen während des Betriebs verwenden, immer noch ein Diskussionsthema. Heute gibt es viele vorliegende Ergebnissezur Charakterisierung der Brucheigenschaften von Klebstoffen unter reinen Modus I und II, das Versagensverhalten unter Mischbeanspruchung ist hingegen Bestandteil von nur sehr wenigen Arbeiten.

Innerhalb der vorliegenden Arbeit wird das Versagensverhalten eines duktilen Klebstoffs unter Mischbeanspruchung, mit Hilfe des sog. Mixed-Mode Bending Test (MMB) untersucht. Zu diesem Zweck werden experimentelle, analytische und numerische (Finite-Elemente (FE)-Methode) Unteruschungen durchgeführt. Zur Bestimmung der Strain Energy Release Rate (SERR) der Klebstoffe basierend auf Ergebnissen des MMB-Versuchs wird eine geschlossene Formelbeziehung auf der Basis des äquivalenten Biegemoduls und der äquivalenten Risslänge entwickelt. Diese ist in der Lage die sich bildenden nichtlinearen Effekte in der Rissspitze zu erfassen. Diese Methode ist unabhängig von der Überwachung der Risslänge. Zusätzlich wird eine kürzlich entwickelte verbesserte J-Integralmethode zur Bestimmung der SERR für in der vorliegenden Arbeit verwendeten Klebstoff implementiert. Diese Methode ist nicht von den elastischen Eigenschaften des Klebstoffs, den Haftmitteln, den Rissmessungen, der Nachgiebigkeit des Systems usw. abhängig, wodurch die Genauigkeit der gemessenen Bruchenergien enorm verbessert werden kann. Zusätzlich wird der Einfluss der Klebschichtdicke auf die ermittelte kritische SERR (CSERR) untersucht. Es wird beobachtet, dass die experimentell ermittelte CSERR im Gegensatz zum reinen Modus I, unter Mischbeanspruchung nicht sehr stark von der Klebschichtdicke abhängig ist.

In dieser Arbeit werden Finite-Elemente-Modelle für unterschiedliche Zwecke entwickelt: zur Bestimmung der CSERR (unter Verwendung der J-Integralkontur), zum Benchmarking der Vorhersage von Versagenslasten in Klebverbindungen unter Mischbeanspruchun und zur Validierung der in dieser Arbeit verwendeten analytischen Ansätze.

Contents

Nomenclature

Abbreviations

CSERR	**C**ritical **S**train **E**nergy **R**lease **R**ate
CZM	**C**ohesive **Z**one **M**odel
COD	**C**rack **O**pening **D**isplacement
DCB	**D**ouble **C**antilever **B**eam
DIC	**D**igital **I**mage **C**orellation
ECLM	**E**quivalent **C**rack **L**ength **M**ethod
ENF	**E**ouble **N**otched **F**lexure
ELS	**E**nd **L**oaded **S**plit
FEM	**F**inite **E**lement **M**ethod
FPZ	**F**racture **P**rocess **Z**one
LEFM	**L**inear **E**lastic **F**racture **M**echanics
LVDT	**L**inear **V**ariable **D**ifferential **T**ransformers
MC-DCB	**M**ixed-mode **C**ontrolled- **D**ouble **C**antilever **B**eam
MMB	**M**ixed **M**ode **B**ending
MMR	**M**ixed **M**ode **R**atio
SERR	**S**train **E**nergy **R**lease **R**ate
SHM	**S**tructural **H**ealth **M**onitoring
SDI	**S**tructural **D**amage **I**ndicator
SIF	**S**tress **I**ntensity **F**actor
SLJ	**S**ingle **L**ap **J**oint
TDCB	**T**aperd **D**ouble **C**antilever **B**eam
TSL	**T**raction **S**eparation **L**aw
VCCT	**V**irtual **C**rack **C**losure **T**echnique
XFEM	e**X**tended **F**inite **E**lement **M**ethod
ZSP	**Z**ero **S**train **P**oint

Arabic alphabetic characters

a	Crack length
a_0	Initial crack length
a_e	Equivalent crack length
b	Width of specimen
C	Compliance
c	Lever distance
E	Elastic modulus
E_b	Bond energy
E_{eq}	Equivalent modulus of elasticity
$F_\alpha(X)$	Asymptotic crack tip function
G	Shear modulus
G_C	Critical strain energy release rate (fracture toughness)
G_{equiv}	Equivalent strain energy release rate (fracture toughness)
$G_{I,II,\ III}$	Strain energy release rate in mode I, II and III
$G_{IC,IIC,\ IIIC}$	Critical strain energy release rate in mode I, II and III
H(X)	Discontinuous jump function
h	Height of the adherend
I_{ij}	Moment of inertia element
J	J-integral
K_I	Mode I stress intensity factor
k	Bond stiffnes
L	Half span length
M_{ij}	Bending moment element
$N_I(X)$	FE shape functionsy
P	Applied force
P_m	Maximum applied force
$R_{p0.2}$	Yield stress
T	Cohesive traction in load introduction points
T_i	Traction vector
t	Thickness of the adhesive layer

t_n	Traction in pure normal direction
$t^0{}_n$	Maximum traction in pure normal direction
t_s, t_t	Traction in shear directions
$t^0{}_s$, $t^0{}_t$	Maximum traction in shear directions
u,w	Horizontal and vertical components of the displacement vector
$u^h(X)$	Finite element displacement approximation
u_I	Nodal degree of freedom
w	Strain energy density

Greek alphabetic characters

α,β	Correction parameters
Γ_i	Integration path
γ_s	Surface energy
Δ	Crack length correction
δ	Displacement
δ_c	Critical displacement
δ_f	Failure displacement
θ_i	Rotation angles in load introduction points
ν	Poisson's ratio
σ_c	Cohesive stress
σ_{ij}	Stress tensor element
χ	Correcting factor for the crack length
ψ	Nominal phase angle of loading