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Experimental and numerical failure analysis of notched quasi-unidirectional laminates at room temperature and elevated temperature

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ABSTRACT

In this work an approach to predict the strength of notched structures made of quasi unidirectional glass fibre epoxy is presented. It takes into account the fabric specific behaviour in terms of hardening and softening. Four macroscopic ply failure modes are considered according to the Hashin criterion, depending on the direction of loading. Material hardening and softening is implemented according to Continuum Damage Mechanics. The hardening mechanism is modelled separately for matrix tension and shear. The softening mechanism is modelled by the incorporation of fracture toughness according to the failure mode (fibre/matrix failure in tension/compression). A new technique is proposed to determine the fracture toughness from uniaxial tension/compression tests of unidirectional notched laminate specimens. Special interest is given to the temperature impact on the material properties (elastic parameters, strengths and fracture energy) in a wide range (-40 °C to 160 °C). Since the interval covers the rubber temperature of epoxy the approach's reliability under such conditions is examined as well.

1. Introduction

The low specific weight of continuous fibre reinforced plastics (FRP) offers light weight design opportunities. Therefore, the application of FRP materials in automotive engineering is increasing since the year 2000, as shown by Lässig [1]. Carbon fibre composites approved well in lightweight structures. Glass fibre epoxy composites are candidates for cost sensitive applications due to low production cost. Unidirectional (UD) plies fail catastrophically at low stresses when loaded transversely to the fibre. This shortcoming is not present at balanced woven fabric. But their mechanical proprieties in warp and weft direction are reduced by towel crimp (undulation) which is described Puck [2]. As a result they reach low strengths, compared to fibre parallel loaded UD plies with the same fibre fraction. In quasi UD woven fabric towel crimp is less serious, which significantly improves their mechanical properties as described by Schürmann [3] and Karahan [4]. Quasi UD refers to strongly unbalanced fabric, where usually around 90% of fibres are aligned in warp direction. Quasi UD fabric combines the advantages of UD composites and balanced fabric: Good mechanical properties in fibre direction, a medium failure strain when loaded fibre transversely and a very high failure strain when loaded mainly by shear. This reduces the probability of catastrophic failure. To use the benefits of quasi UD glass fibre epoxy (GF-EP) fabric in structural application, a model is presented predicting the failure of notched structures under quasi-static loading. Since epoxy resin is sensitive to elevated temperatures, the model is validated for room and high temperatures. The influence of fibre volume fraction on the material properties is considered as well.

2. State of the art

2.1. Experimental

The mechanical behaviour of FRP is very different from metals since it is anisotropic and inhomogeneous. The failure of FRP is not determined by a single crack mechanism and its propagation but rather by several damage mechanisms. In the last years intense research revealed the failure phenomena of balanced, moderately unbalanced and quasi UD woven fabric.

Roy [5] examined unbalanced woven carbon fibre epoxy (CF-EP) fabric with a fibre ratio of 6:1 and compared it to a model laminate, which only contained crimp in warp direction. Lomov [6] examined triaxially woven and quasi UD fabric. The triaxial fabric is based on CF, placed longitudinally and in ±45° direction, which is

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Nomenclature

Abbreviations

FRP	fibre reinforced plastics
CF	carbon fibre
GF	glass fibre
EP	epoxy
UD	unidirectional
MD	multidirectional
FVF	fibre volume fraction
CLT	Classical Laminate Theory

Symbols and parameters

φ	fibre volume fraction
T	temperature
σ	Cauchy stress
E	elastic Modulus
G	shear Modulus
H	hardening Modulus
r	material strength
D	damage parameter
G	fracture toughness
g	failure energy density
l	length

Indices

f	fibre
m	matrix
t	tension
c	compression
tan	tangent modulus
y	yield
0	initial ultimate
eq	equivalent
cri	critical
th	threshold
un	unnotched
FEM	Finite Element Method
CDM	Continuum Damage Mechanics
SR	stiffness reduction
RT	room temperature
HT	high temperature
E-Machine	Electric Machine
APDL	Ansys Parametric Design Language
ε	infinitesimal strain
υ	Poisson's ratio
C	stiffness
A	area
n	number
l	length
d	hole diameter
w	specimen width
F	specimen strength
Δ_{target}	optimization target
1	longitudinal to warp fibres
2	in ply transverse to warp fibres
3	out of ply transverse to warp fibres
El	element
IP	integration point
cra	crack
chr	characteristic
exp	experiment
sim	simulation
no	notched

embedded in EP. In the quasi UD fabric, not only the fibre ratio was strongly unbalanced, also the warp contained CF and the weft GF. Bonnafous [7] examined balanced hemp fibre epoxy fabric. Damage mechanisms were acoustically measured on component level and compared to acoustic emissions of the fabric. Daggumati [8] examined balanced fabric consisting of GF and a thermoplastic matrix. Damage initiation and progress were acoustically and visually measured. It revealed how the damage mechanism of a ply is influenced by its position in the laminate. Kergomard [9] examined the influence of crimping on damage mechanisms in quasi UD fabric, which consists of GF-EP with fibre ratio of 87:13. Kasrahan [4] examined the influence of fibre crimp on the mechanical ply properties of six fabrics types with an epoxy matrix. Carbon, Aramid and Glass fibres were used. The quasi UD fabric consists of a carbon fibre warp with a local fibre volume fraction (FVF) of 0.51 and a glass fibre weft. Kersani [10] examined quasi UD fabric consisting of flax and epoxy with a fibre ratio of 955:45. The beginning of failure in different laminate layups is acoustically measured and compared to the stress strain curves.

Even though structure and components of the examined fabrics vary, similar damage mechanisms occur. Damage progression in fabric generally is a multilevel phenomenon, it occurs on the microscale (fibre, matrix and interface), mesoscale (woven unit cell or ply level) and macroscale (laminate level).

According to Puck [2] the fabric failure mechanisms on the microscale are the same as in UD plies: In longitudinally loaded plies, single fibres break before the load reaches the ply strength. As described by Schürmann [3] and Talreja [11] this is caused by the statistical distribution of fibre defects. From this point, cracks either propagate along the fibre or load perpendicular into the matrix. As matrix cracks reach adjacent fibres and circumvent them, they cause fibre bridging. Nevertheless most fibres remain intact, explaining a nearly constant ply stiffness, until the load reached the ply strength. At the ply strength, fibre fracture accelerates causing ply stiffness degradation. Due to statistical distribution of the fibre strength and fibre pull out, cohesive behaviour is observed until final failure. In transversally loaded plies cracks nucleate at matrix flaws or fibre matrix interfaces (debonding). A single crack rapidly splits the (isolated) ply, growing load perpendicular within the matrix and along interfaces. The ply's stiffness remains constant until it fails in a brittle mode.

According to Lomov [6], Daggumati [8] and Bonnafous [7] the woven unit cell's failure phenomenology can be classified into certain stages:

- Damage initiation occurs in transversely loaded towels (microcracks) or at towel crossings (micro-delamination).
- Damage progression includes microcrack stopping at adjacent towels, crack propagation at towel crossings, and crack combination.
- The final failure mechanism is breakage of the towels in loading direction. This is to large extent driven by the separation of crossing towels through micro-delamination.

Lomov [6] observes a nonlinear stress strain curve for fibre inclined loaded quasi UD plies. The yield point corresponds to the occurrence of acoustically measured damage. The ply failure modes are similar to those of UD plies. Karahan [4] loads the quasi