Apparatus and Method for Characterization of Bonded Joints Mixed Mode I+II Fracture
motivation

predict the structure toughness

joint mechanical behavior

strain energy release rate in mode I, mode II and mixed-mode I+ II
determination of the strain energy release rate in mode I, mode II and mixed mode I + II
Fracture toughness of a structural adhesive under mixed mode loadings, Mat.-wiss. u.Werkstofftech. 2011, 42, No. 5, 460-470

<table>
<thead>
<tr>
<th>Test name</th>
<th>Test scheme</th>
<th>Global Mixity, $\psi$ (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asymmetric Double Cantilever Beam (ADCB)</td>
<td><img src="ADCB-schematic.png" alt="ADCB schematic" /></td>
<td>$\approx 0 - 34^\circ$</td>
</tr>
<tr>
<td>Single Leg Bending (SLB)</td>
<td><img src="SLB-schematic.png" alt="SLB schematic" /></td>
<td>$\approx 41^\circ$</td>
</tr>
<tr>
<td>Crack Lap Shear (CLS)</td>
<td><img src="CLS-schematic.png" alt="CLS schematic" /></td>
<td>$\approx 49^\circ$</td>
</tr>
<tr>
<td>Asymmetric Tapered Double Cantilever Beam (ATDCB)</td>
<td><img src="ATDCB-schematic.png" alt="ATDCB schematic" /></td>
<td>$\approx 20^\circ$</td>
</tr>
<tr>
<td>Mixed Mode Bending (MMB)</td>
<td><img src="MMB-schematic.png" alt="MMB schematic" /></td>
<td>$\psi = f(c)$</td>
</tr>
<tr>
<td>Spelt Loading Jig (SPELT)</td>
<td><img src="SPELT-schematic.png" alt="SPELT schematic" /></td>
<td>$\psi = f(S_1, S_2, S_3, S_4)$</td>
</tr>
</tbody>
</table>

$$\psi = \arctan \left( \sqrt{\frac{G_u}{G_I}} \right)$$
Virginia Tech’s Dual Actuator Loading Frame

Pure modes [ I and II ]

DCB

ENF

37th Annual Meeting

San Diego 2014.26.02

Design methodology

Simulation

finite element analysis

Parts and assemblies

Data reduction scheme and experimental results

3D model

SolidWorks
design methodology
model – Solidworks®
loading scheme

\[ h = 12.7 \text{ mm} \]
\[ 2L = 260 \text{ mm} \]
\[ b = 25 \text{ mm} \]

mode separation

The specimen geometry is in accordance with the ASTM D3433-99

(DCB)

(EENF)
Steel properties used for substrates and Jig base

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (HB)</th>
<th>Yield Stress (MPa)</th>
<th>Ultimate Fracture Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AISI P20</strong></td>
<td>290/330</td>
<td>640</td>
<td>993</td>
</tr>
<tr>
<td><strong>DIN CK 45</strong></td>
<td>170</td>
<td>323</td>
<td>578</td>
</tr>
</tbody>
</table>

Spelt problem size in ABAQUS®

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>92199</td>
</tr>
<tr>
<td>Number of nodes defined by user</td>
<td>86547</td>
</tr>
<tr>
<td>Number of elements</td>
<td>79380</td>
</tr>
<tr>
<td>Number of elements defined by user</td>
<td>76551</td>
</tr>
<tr>
<td>Internal nodes generated by program</td>
<td>5652</td>
</tr>
<tr>
<td>Internal elem. generated for contact</td>
<td>2826</td>
</tr>
<tr>
<td>Number of variables in the model</td>
<td>268128</td>
</tr>
</tbody>
</table>
Fracture envelope for the seven scenarios considering the linear (•) and quadratic (□) criteria.

- Quadratic (criterion)
  \[ \left( \frac{g_I}{g_{Ic}} \right)^2 + \left( \frac{g_{II}}{g_{IIc}} \right)^2 = 1 \]

- Linear (criterion)
  \[ \left( \frac{g_I}{g_{Ic}} \right) + \left( \frac{g_{II}}{g_{IIc}} \right) = 1 \]

Different scenarios used for the fracture envelope calculation

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>s₁ (mm)</th>
<th>s₂ (mm)</th>
<th>s₃ (mm)</th>
<th>s₄ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>100</td>
<td>40</td>
<td>140</td>
<td>-60</td>
</tr>
<tr>
<td>P₂</td>
<td>120</td>
<td>40</td>
<td>160</td>
<td>-120</td>
</tr>
<tr>
<td>P₃</td>
<td>40</td>
<td>120</td>
<td>160</td>
<td>40</td>
</tr>
<tr>
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<td>140</td>
<td>60</td>
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<tr>
<td>P₅</td>
<td>60</td>
<td>80</td>
<td>140</td>
<td>120</td>
</tr>
<tr>
<td>P₆</td>
<td>40</td>
<td>40</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>P₇</td>
<td>100</td>
<td>40</td>
<td>140</td>
<td>80</td>
</tr>
</tbody>
</table>
improved geometry for a smaller size spelt apparatus using the same DCB specimen
displacements: $\delta_1, \delta_2$

load: $F$
crack length is difficult to read

visual assessment does not account for the FPZ

data reduction scheme using CBBM
Load vs. Displacement curves for a \( \psi = 85^\circ \) combination

\[
\psi = \arctan \left( \sqrt{G_{II}/G_1} \right); \quad \psi = \arctan \left[ \frac{\sqrt{3}}{2} \left( \frac{F_1}{F_2} + 1 \right) \right]
\]

85°
R-curves ($G_I$ and $G_{II}$) for a $\psi = 85^\circ$ combination
mixity variation ($G_I / G_{II}$) for a $\psi = 85^\circ$ combination
Fracture envelope for three experiments

- Linear criterion
- $\psi = 85^\circ$
- $\psi = 20^\circ$
- $\psi = 0^\circ$
Load vs. Displacement curve for “classical” DCB and “apparatus” DCB

- DCB (da Silva, Esteves et al. 2011)
- Apparatus (DCB)

\[ F(N) \]
\[ \delta (mm) \]
Mixed-Mode I + II Test Apparatus

combination

\[ s_1 = 80 \]
\[ s_2 = 80 \]
\[ s_3 = 160 \]
\[ s_4 = -60 \]
this apparatus represents a compact version of the SPELT JIG:
- using a standard DCB specimen (universal and easy to manufacture);
- covers all range of the fracture envelope from mode I to near mode II;
- promotes a self similar crack propagation.

in combination with the proposed data reduction scheme, accounts for the FPZ and does not requires for the crack length to be measured.

the development of the testing apparatus benefited of a design methodology based in numerical simulation using Finite Element Analysis

validation prior to manufacture, avoided errors and allowed optimization of materials and parts geometry

while at simulation stage a data reduction scheme that improves the efficiency of the test was also developed benefitting of the same design methodology

this data reduction scheme was first validated recurring to numerical results and later used to analyze experimental data with good results
the authors would like to thank “Fundação Luso-Americana para o Desenvolvimento” (FLAD) for the support through the project 314/06 2007 and Instituto de Engenharia Mecânica (IDMEC)

we also like to acknowledge the support provided to Virginia Tech by the National Science Foundation (DMR NSF 0415840) in the development of the dual loading frame capable of facilitating mixed mode studies.
thank you

questions?

filipechaves.com/apparatus