Effect of the crack length monitoring technique during fatigue delamination testing on crack growth data

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Framework

An integral approach to account for interlaminar fatigue damage in the design of composite structures

A Turon, J Costa, PP Camanho, CG Dávila
*Simulation of delamination in composites under high-cycle fatigue*
Framework

- An integral approach to account for interlaminar fatigue damage in the design of composite structures.

**SIMULATION**

- How reliable are existing experimental methods for fatigue characterization?
Framework

Crack growth rate under mode I loading.

DCB Double Cantilever Beam

![Diagram of Crack Growth Rate](image)

- Region I: Fatigue threshold
- Region II: Crack growth rate
- Region III: Static failure

Parameter:
- \( \frac{da}{dN} \) (mm/cycle)
- \( G_{\text{max}} \) (J/m²)

Equation:

\[
\frac{da}{dN} = G_{\text{max}} \]

Symbols:
- \( da \): Crack extension
- \( dN \): Number of cycles
- \( G_{\text{max}} \): Maximum energy release rate
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Crack growth rate under mode I loading.

Tests typically performed under controlled displacement and constant amplitude ($\delta_{\text{max}}, \delta_{\text{min}}$)
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Crack growth rate.

A set of \( a(N) \) points is needed to get \( da/dN \)

Crack length observed from the edge of the specimen.

Visual inspection to measure “\( a \)”

- Scatter of the data
- Subjective (unless some automation of the image processing is used)
- Menicus shape of the crack front
Framework

Menicus shape of the crack front.
Objective

- Use of Fibre Bragg Grating sensors to monitor the “real crack” during fatigue crack growth and assess the effect of monitoring it through the specimen’s edge.

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Fibre Bragg Sensors

\[ \Delta \lambda = K \varepsilon_{11} \]
Fibre Bragg Sensors

Two Optical Fibers (OF) in each specimen
In each OF: Array of 4 sensors separated 2 mm.
Each sensor: 1mm in length
FBG’s positioning

It shouldn’t be placed too close to the crack plane
FBG’s positioning
FBG’s positioning

- Exact horizontal positioning by means of Optical Low Coherence Reflectometry

![Diagram of FBG's positioning]

**Distance $z_{FBG}$ [mm]**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>FAT1 OF1</th>
<th>FAT1 OF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.08</td>
<td>77.76</td>
</tr>
<tr>
<td>2</td>
<td>78.43</td>
<td>79.83</td>
</tr>
<tr>
<td>3</td>
<td>80.34</td>
<td>81.74</td>
</tr>
<tr>
<td>4</td>
<td>82.45</td>
<td>83.82</td>
</tr>
</tbody>
</table>
Fibre Bragg Sensors
Crack tip detection

Sharp crack. Pure elastic

Fracture process zone. Quasibrittle
FBG strain vs. N

8 \((a_{FBG}, N)\) points for each specimen
$a_{\text{VIS}}$ vs. $N$

Continuous shooting of pictures and post-analysis

40 $(a_{\text{VIS}}, N)$ points for each specimen
Real time monitoring of the compliance, $C(N)$

\[ C = \frac{\Delta \delta}{\Delta P} \]

\[ C = \frac{\delta_{\text{max}}}{P_{\text{max}}} \]
Extrapolation to a continuous $a(N)$

Modified Compliance Calibration:

$$\frac{a}{h} = C^{1/3} A_1 + n$$

![Graph showing extrapolation to a continuous $a(N)$ with data points for VIS and FBG methods.](image)
da/dN vs. $G_{\text{max}}$

\[ G_{\text{Imax}} = \frac{P_{\text{max}}^2}{2B} \frac{dC}{da} \]
Fatigue vs. static data

\[ \frac{da}{dN} \text{ (mm/cycle)} \]

\[ G_{\text{Imax}} \text{ (J/m}^2\text{)} \]

VIP

GIC

PROP

GIC

NL

GIC

5% MAX

GIC
FBG vs. VIS

\[ da/dN \text{ (mm/cycle)} \]

\[ G_{I_{\text{max}}} \text{ (J/m}^2\text{)} \]

- **FBG**
- **VIS**
FBG vs. VIS

\[ \frac{da}{dN} (\text{mm/cycle}) \]

\[ G_{th} \]

\[ G_{th} \]

\[ G_{th} \]

\[ m \]

\[ \begin{array}{|c|c|c|c|}
\hline
\text{Specimen} & \text{Method} & m & G_{Ith} [\text{J/m}^2] \\
\hline
\text{FAT1} & \text{VIS} & 20.57 & 129.93 \\
\text{FAT1} & \text{FBG} & 20.83 & 119.25 \\
\hline
\end{array} \]
FBG vs. VIS

$\frac{da}{dN}$ (mm/cycle) vs. $G_{\text{Imax}}$ (J/m$^2$)

VIS

FBG

$G_{\text{th FBG}}$

$G_{\text{th VIS}}$

$m$
FBG vs. VIS

\[ a \text{ (mm)} \]

\[ N \]

\[ \triangle \text{ VIS computed} \]
\[ \square \text{ FBG computed} \]
\[ \bigcirc \text{ VIS measured} \]
\[ \bigcirc \text{ FBG measured} \]
It is just a constant shift?

\[ \Delta a \]

VIS corrected with constant $\Delta a$
FBG vs. VIS

![Graph showing comparison between VIS computed, FBG computed, VIS measured, and FBG measured results. The graph plots the variability ($\Delta a$) against the cycle number ($N$) with a focus on the progression of $a$ (mm) up to 90 mm.]
The difference between crack length measured by VIS and FBG methods evolves during the test (why?)
Conclusions

- This work has shown the feasibility to apply FBG’s sensors to accurately monitor fatigue tests under mode I loading.
- Fatigue tests are suitable to assess onset static data.
- Monitoring the crack by the edge (VIS) is not a conservative method to generate fatigue data for design:
  - in the material studied, crack growth rate is 10 times lower than the measured with FBG’s
  - threshold energy, $G_{th}$, is 10% higher
- The difference between $a_{VIS}$ and $a_{FBG}$ evolves during the test suggesting that the failure process zone also evolves.
Coming next

- Make use of FBG’s to study the fracture process zone:
  - Evolution during the test
  - Bonded joints
- Analyse fatigue testing under mode II and mixed-mode tests