Numerical Simulation of Fatigue in Composites

Imperial College London

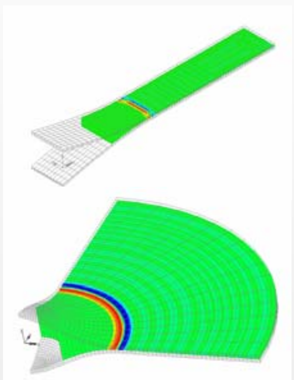
The Composites Centre
for research, modelling, testing and training in advanced composites

Dr. Giordano Bellucci & Davide Tumino
Supervised by
Dr. Ugo Galvanetto & Dr. Paul Robinson

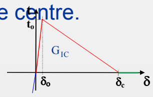
Summary. Fibre composites often consist of layers that are bonded together as part of the curing process. Delamination is the separation of these layers and it is mainly due to edge effects, impact, fatigue or other causes which generate significant interfacial stresses. Delamination can imply catastrophic rupture and exhibit complex failure mechanisms. This phenomenon can be modelled using methods based on Linear Elastic Fracture Mechanics but here attention is focused on a *cohesive-zone* model pioneered by Dugdale & Barrenblatt. The *cohesive-zone* model was successfully applied to numerical simulation by means of a particular type of finite element: the interface element. The use of interface elements for the analysis of interlaminar fracture in composite structures has been widely proposed in the literature. Such a formulation does not account for delamination due to repeated application of a cyclical load. The interface element formulation developed by Professor Crisfield and co-workers has been here developed further to allow propagation of cracks in laminated composites caused by cyclic loading. The main idea consists of coupling together the long-term effect of fatigue with instantaneous delamination occurring as a result of overloads. The framework has been implemented into the Finite Element implicit code LUSAS and numerical results are compared with experimental tests demonstrating a good agreement.

1. Delamination in composites

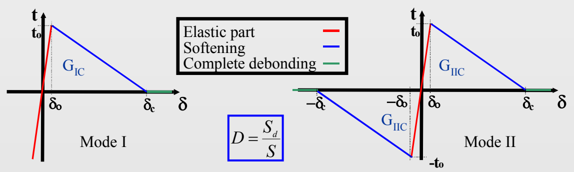
The interface element formulation developed by Professor Crisfield has been successfully applied in classical specimens such as the Double Cantilever Beam (DCB), for the investigation of delamination in composite laminates. The figure shows two numerical simulations of delamination in a DCB and in a plate with a circular crack in the centre.



Traction-displacement behaviour of the mid-plane for the DCB and the circular specimens.



2. Fatigue in Interface Elements



$$D = \frac{S_d}{S}$$

- In the finite element formulation, a constitutive law is required between the stress vector **t** and the relative displacement δ.
- To combine delamination with a fatigue model, the rate of damage is expressed as the sum of two terms:

$$\Delta D_{tot} = \Delta D_{stat} + \Delta D_{fat}$$

Static + fatigue delamination

- Applying a cyclic load, it is convenient to consider the Damage development as a function of the number of cycles N:

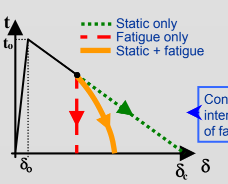
$$\Delta D_{stat} = \frac{\delta_c \delta_0}{\delta_c - \delta_0}\left(\frac{1}{\delta_N} - \frac{1}{\delta_{N+\Delta N}}\right)$$

Static delamination only

- A modified version of the damage propagation law proposed by de Borst for continuum mechanics has been here introduced to simulate crack propagation between plies caused by high-frequency cyclic load:

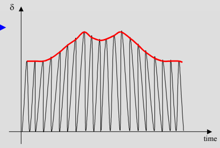
$$\Delta D_{fat} = \Delta N \frac{C}{\beta + 1} e^{\lambda D_{\mu}} \left(\frac{\delta_{\mu}}{\delta_c}\right)^{\beta+1}$$

Fatigue delamination only

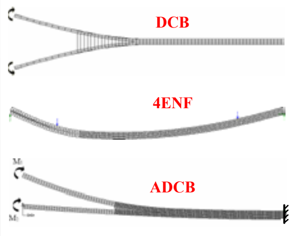


Constitutive behaviour of the interface element in presence of fatigue

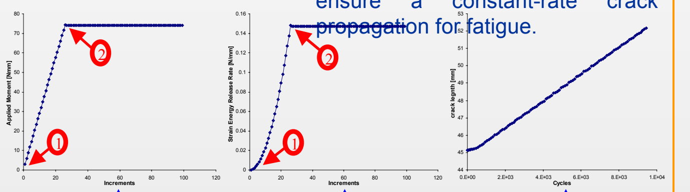
In computing the damage rate for fatigue the envelope of the load history is used.



3. Numerical examples



Numerical simulations have been performed in cases of pure Mode I (Double Cantilever Beam), pure Mode II (4-point End Notched Flexural specimen) and Mixed Mode (Asymmetric Double Cantilever Beam) with different values of mode mixity G_I/G_{II}. The specimens and load are chosen to ensure a constant-rate crack propagation for fatigue.



Applied moment at the tip of the DCB. (1) progressive increase of load without fatigue, (2) the applied load is maintained constant and cyclic fatigue starts.

Computed value of the SERR G_I for the DCB. (1) increase of G_I without fatigue, (2) cyclic fatigue starts and the energy released remains constant.

Fatigue Crack propagation with cycling. Points can be fitted with an interpolation line from which the value of *da/dN* for the applied *G* can be calculated.

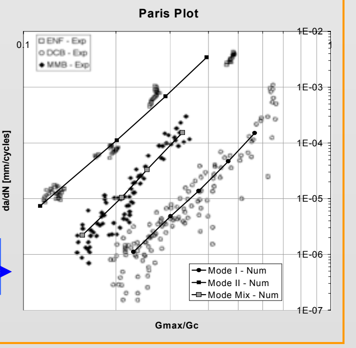
Similar diagrams are obtained for mode II and mixed cases.

4. Comparison with experiments

With this numerical model it is possible to simulate the linear portion of fatigue-life of a structure, i.e. the field where the modified Paris law applies:

$$\frac{da}{dN} = B(G_{max})^m$$

To obtain the correct Paris plots for each mode, optimal parameters in de Borst's law can be found using a few experimental data points.



Comparison of numerical results with experimental data by Greenhalgh *et al.* for delamination fatigue in Mode I, Mode II and Mixed Mode (G_I/G_{II}=1)

Conclusions and future works

- A cyclic damage model has been implemented in an interface element to simulate fatigue delamination between the plies of a composite.
- The model simulates the crack propagation for fatigue in single and mixed modes.
- Modelling the transition from the threshold G_{th} is currently under investigation.

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