MODELLING FATIGUE DELAMINATION PROPAGATION IN LAMINATED COMPOSITES WITH AN INCREMENTAL FATIGUE ONSET STRATEGY

Man Zhu[1,2], Larissa Gorbatikh[1,2] and Stepan V. Lomov[1,2]

[1]Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44 bus 2450, 3001 Leuven, Belgium
Email: man.zhu@kuleuven.be, larissa.gorbatikh@kuleuven.be, stepan.lomov@kuleuven.be, Web Page: http://www.composites-kuleuven.be/
[2]SIM M3 program, Technologiepark 935, 9052 Zwijnaarde, Belgium
Web Page: http://www.sim-flanders.be/

Keywords: Fatigue delamination, delamination onset, delamination propagation, cohesive zone models

Abstract
In this paper a fatigue cohesive zone model (CZM) is developed for simulation of fatigue delamination propagation in composite laminates. The propagation is modelled as a sequence of incremental onset events. A progressive damage law, controlling the fatigue damage accumulation, is proposed based on the G-N curve measured in fatigue delamination onset tests. Unlike current CZMs relying on the assumption of Paris' law, all input parameters of the proposed CZM are solely based on the G-N curve. Paris' law is objectively predicted by the model. The model is applied to Mode I fatigue loading and compared with experimental data.

1. Introduction

Cohesive zone models (CZMs) have been widely used to model fatigue delamination, mainly due to their success in quasi-static simulations and computational efficiency. In these models, a layer of cohesive elements is introduced along a potential delamination path, and failed cohesive elements indicate propagation of the delamination. The greatest challenge of developing a CZM lies in the mathematical description of the progressive degradation law controlling damage accumulation in the cohesive elements as they undergo cyclic loading.

In majority of the existing CZMs, the progressive degradation law is based on Paris' law obtained from fatigue delamination propagation tests [1-3]. The Paris' law is a macroscopic description of the delamination growth, while in the CZMs it is applied locally. On the other hand, the fatigue delamination onset test, which measures the number of cycles N required for an existing crack to start growing under a certain strain energy release rate (SERR) G by applying load or displacement, is directly linked to the local phenomena occurring ahead of the crack tip. From this point of view, the output of the onset test, the G-N curve, is better suited for definition of a CZM being in line with its local concept.

A new fatigue CZM for the simulation of fatigue-driven delamination is presented in this paper. The G-N curve shows that the critical strain energy needed to initiate a new crack surface decreases with the number of loading cycles. Based on the degradation of the critical SERR, a progressive degradation law is developed to simulate the fatigue damage accumulation in cohesive elements. The failure of a single cohesive element represents the fatigue delamination onset and the propagation is simulated as a sequence of successive onsets in the cohesive elements.

2. CZM description

The G-N curve obtained from the fatigue delamination onset test, as shown in Fig. 1 [4], describes the number of loading cycles N_{onset} needed for fatigue onset with different applied SERR G_{max}. It indicates that the required SERR to form a new crack surface, G_c, decreases from the static fracture toughness $G_{c(static)}$ to G_{max} after N_{onset} loading cycles. Therefore, the damage accumulation caused by fatigue loading can be described as the degradation of G_c.

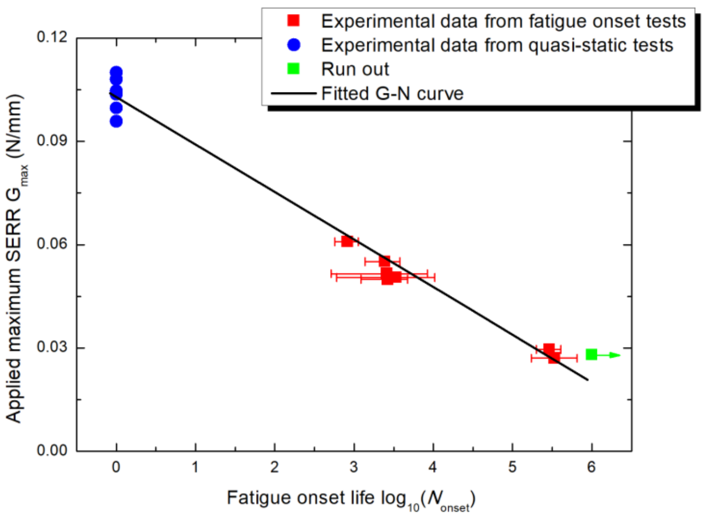

Figure 1. The G-N curve from fatigue delamination onset tests [4].

A bilinear constitutive law was adopted to describe the interfacial behaviour under static loading as shown in Fig. 2(a). K_0 is the initial stiffness, $\delta_{0(static)}$ and $\delta_{f(static)}$ stand for the displacement corresponding to damage initation and failure under quasi-static loading, respectively. The area under the traction-separation curve represents the strain energy dissipated upon formation of a unit of a new crack surface, and is equal to the fracture toughness $G_{c(static)}$ for static case.

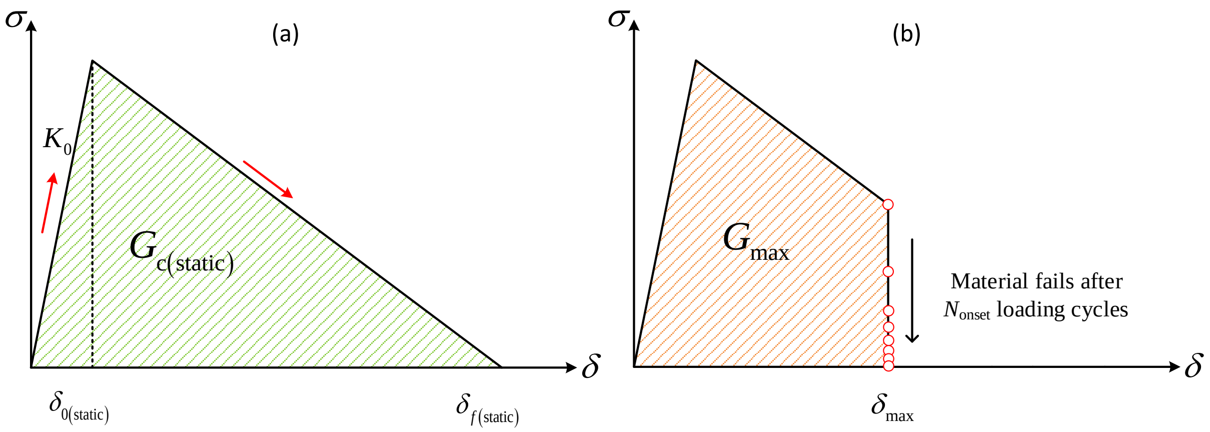

Figure 2. (a) Bilinear constitutive law of cohesive element for static loading; (b) Constitutive law of cohesive element for fatigue loading with constant maximum SERR G_{max}.

For the case of fatigue loading, as the number of loading cycles increases, the fatigue damage accumulates in the material and the required SERR for new crack surface formation, G_c, decreases. A logritham degradation law is proposed to calculate the degraded G_c with the number of loading cycles N:

$$\frac{\mathrm{d}G_c}{\mathrm{dln}N} = \frac{G_{max} - G_{c(static)}}{\ln N_{onset}} \Rightarrow \frac{\mathrm{d}G_c}{\mathrm{d}N} = \frac{G_{max} - G_{c(static)}}{N \ln N_{onset}} \quad , \tag{1}$$

where (N_{onset}, G_{max}) corresponds to a point on the G-N curve. The area under the constitutive cohesive law curve is then degraded based on the decrease of G_c. Fig. 2(b) shows that the total area under the traction-separation curve decreases to the applied maximum SERR G_{max} when the material has failed after N_{onset} cycles. The failure displacement equals to the applied maximum displacement, δ_{max}. Cohesive elements are placed at the potential path of delamination, and the proposed degradation law is implemented into the cohesive elements. The failure of each cohesive element is modelded as the delamination onset, and the delamination propagation is then simulated as the successive failure of the cohesive elements, i.e. incremental onsets.

3. Result and discussion

The developed CZM was implemented as a user defined material subroutine in finite element (FE) software and the mode I fatigue delamination propagation was simulated. The latter was done for the double cantilever beam (DCB) set up. The arms of DCB were composed of 8-node solid elements; the interface between the arms was modeled with help of 8-node cohesive elements. Only one element was modelled along the width direction and a state of generalised plane strain was assumed, which means the front and back edge of the specimen, shown in Fig. 3, are kept parallel during the deformation.

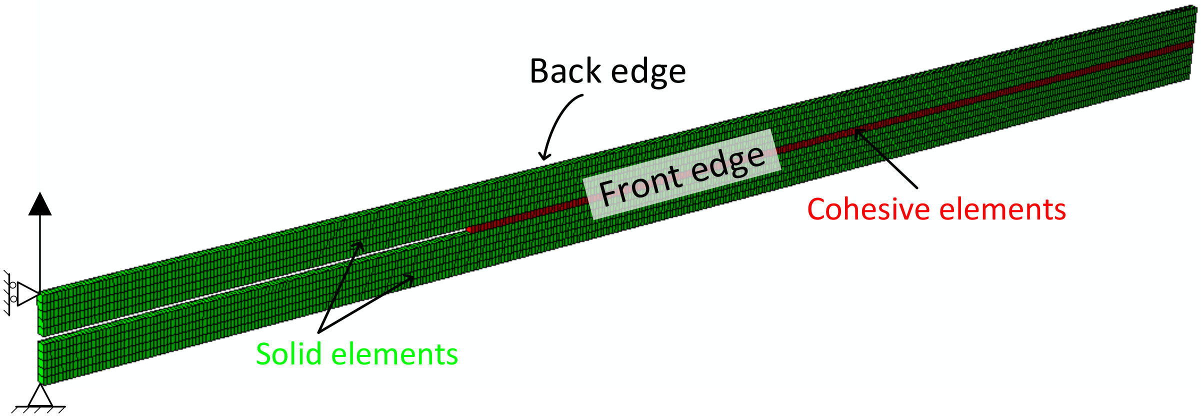

Figure 3. FE model of DCB specimen and boundary conditions .

The elastic properties of the simulated carbon/epoxy UD laminates and the interlaminar properties of $0^o//0^o$ interface are shown in Table 1, where direction 1 stands for the fibre direction. The fitted G-N curve in Fig. 1 obtained from the fatigue onset test was used as input of the material properties:

$$G_{max} = a\ln\left(N_{onset}\right) + b\,. \tag{2}$$

where a and b are fitting parameters.

Table 1. Material properties of carbon/epoxy UD laminates.

Elastic properties	E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$ (-)	ν_{23} (-)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)
	126	9.4	0.3	0.3	4.1	3.31

Interlaminar properties	$G_c\vert_{static}$ (N/mm)	$\sigma_0\vert_{static}$ (MPa)	a (N/mm)	b (N/mm)
	0.104	71	-0.0062	0.1029

The model was firstly loaded to the maximum displacement statically. Once the maximum displacement was reached, the number of loading cycles starts to be counted, and the maximum displacement is maintained during the whole simulation. The fatigue delamination propagation is determined by the successive failure of cohesive elements. In Fig. 3, the simulated fatigue delamination propagation rate under different loading levels are compared with the expereimental data previously reported by the authors [5]. The new CZM can predict the slope of the Paris' law successfully. Further research is needed to understand the overall lower propagation rate predicted by the model.

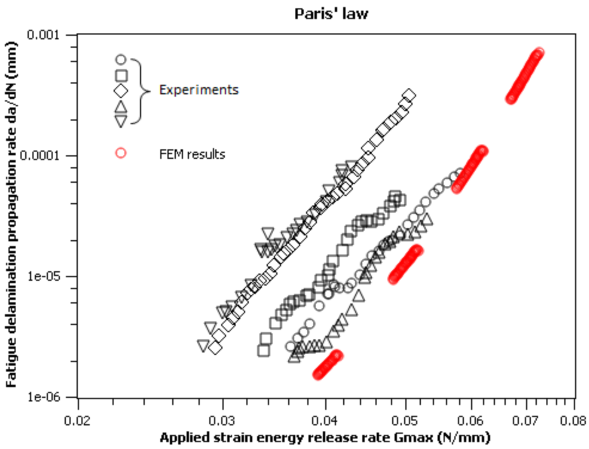

Figure 4. Comparisson of FEM simulation and experimental results [5] of Mode I fatigue delamination propagation.

4. Conclusion

A new CZM is proposed to simulate fatigue delamination propagation in composite laminates. In this CZM, the fatigue delamination propagation is modeled as a sequence of incremental onsets – an approach that fits well with the local concept of cohesive elements. The input data for the model rely on fatigue delamination onset tests without prior assumption of Paris' law which describes the fatigue delamianiton propagation behaviour. Instead, the Paris' law is objectively predicted by the proposed CZM.

Acoknowledgement

The work has been funded by the SBO project "M3Strength", which fits in the MacroModelMat (M3) research program funded by SIM (Strategic Initiative Materials in Flanders) and VLAIO (Flanders Innovation & Entrepreneurship). We would like to thank Sand Fonteyn, Prof. Lincy Pyl and Prof. Danny Van Hemelrijck from Vrije Universiteit Brussel for the experimental studies, Dr. Delphine Carrella-Payan from Siemens PLM for all the constructive discussions, Honda R&D Co., Ltd. And Mitsubishi Chemical Corporation for the provided material. S.V. Lomov holds Toray Chair for Composite Materials at KU Leuven, support from which is gratefully acknowledged.

References

[1] A. Turon, J. Costa, P.P. Cam.nho and C.G, Dávila. Simulation of delamination in composites under high-cycle fatigue. *Composites Part A: Applied Science and Manufacturing*, 38(11): 2270-2282, 2007.

[2] P.W. Harper and S.R. Hallett. A fatigue degradation law for cohesive interface elements – development and application to composite materials. *International Journal of Fatigue*, 32(11): 1774-1787, 2010.

[3] C. Tao, J. Qiu, W. Yao and H. Ji. A novel method for fatigue delamination simulation in composite laminates. *Composites Science and Technology*, 128: 104-115, 2016.

[4] M. Zhu, L. Gorbatikh, S. Fonteym, L. Pyl, D. Van Hemelrijck and S.V. Lomov. Mode I fatigue delamination growth onset in fibre reinforced composites: experimental and numerical analysis. *Proceedings of the 21st International Conference on Composite Materials ICCM-21*, *Xi'an, China*, August 20-25 2017.

[5] M. Zhu, L. Gorbatikh, S. Fonteym, L. Pyl, D. Van Hemelrijck, D. Carrella-Payan and S.V. Lomov. Digital Image Correlation Measurements of Mode I Fatigue Delamination in Laminated Composites. *Proceedings of the 18th International Conference on Experimental Mechanics ICEM-18*, *Brussels*, *Belgium*, July 1-5 2018.