# MODELING FATIGUE-DRIVEN DELAMINATION USING A THICK LEVEL SET INTERFACE MODEL

M. Latifi[1], F.P. van der Meer, L.J. Sluys

Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, Netherlands
[1] Email: m.latifi@tudelft.nl

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**Abstract**
This paper presents a new discontinuous damage model for simulating fatigue-driven delamination in composites. Fatigue models commonly describe crack growth using the Paris law which provides the link between the energy released due to delamination and the crack growth rate. A core issue in implementing the Paris law is to accurately compute the energy release rate. In common cohesive fatigue models the energy release rate is extracted locally from the cohesive law where improving the accuracy of computed energy release rate needs extra treatments. The new fatigue model proposed in this paper provides an accurate non-local method for extracting the energy release rate based on the thick level set approach. This model also profits from the kinematic capabilities of interface elements for modeling discontinuities along the interface. The model is validated by comparing the model predictions under different fracture modes with theoretical and experimental data which shows good agreement in all cases.

## 1. Introduction

Delamination is a common mode of failure in laminated composites under quasi-static and fatigue loading conditions. To ensure the safety of composite structures at the service work predicting their fatigue behavior is necessary. To predict delamination the cohesive zone method has been widely applied by means of interface elements. This method was used for delamination modeling under quasi-static loading and later extended to fatigue analysis [1–5]. For this extension, the energy released due to delamination is extracted from the cohesive law, and the computed energy is used to obtain the crack growth rate according to the Paris law. However, limitations arise in application of this method because of inaccuracy in local extraction of energy release rate [6], and the need for estimating the length of cohesive zone ahead of the crack tip based on geometry and loading conditions [7] . Kawashita and Hallett [7] improved the method by developing a crack tip tracking algorithm which eliminates the dependency of the method on the length of the cohesive zone. This algorithm was applied to orthogonal meshes, and recently Xu and Wang [8] proposed a new crack tip tracking algorithm which is applicable to both orthogonal and non-orthogonal meshes; however, convergence problems restrict the applicability of this model. In earlier work [6] on fatigue analysis we have proposed an alternative for cohesive zone method in the framework of fracture mechanics. This 3D level set model was able to predict fatigue delamination growth rate and its front shape accurately. However, this model is only applicable for simulating single delamination in thin structures. In this paper following the thick level set (TLS) approach [9, 10] a new method for delamination modeling under fatigue is proposed and validated for different fracture modes. The TLS method enables a non-local computation of energy which provides a better match with the Paris law. In this method a damaged band with a predefined length is located between sane and fully damaged material. The non-locality in computing energy appears by integrating local values of energy across the

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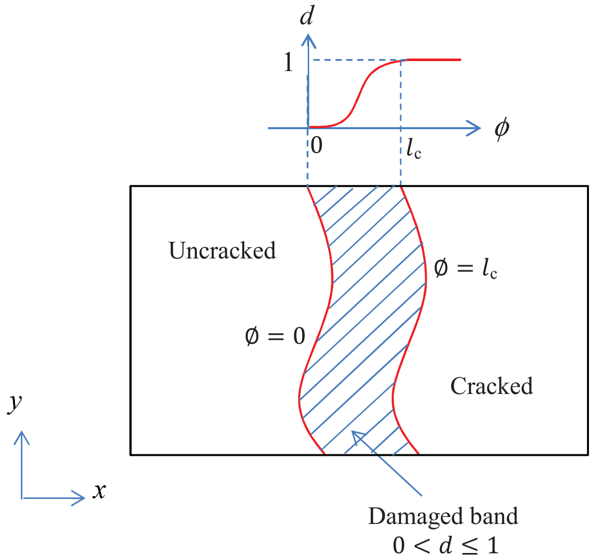


**Figure 1.** Damaged zone between cracked and uncracked material

damaged band. In this paper a combination of the thick level set method and interface elements is used to develop a new discontinuous method for modeling fatigue driven delamination in composite.

## 2. Method

To define the damage parameter, a length scale ($l_c$) is considered which determines the size of the damaged zone between the delaminated and non-delaminated parts of the interface (see Fig. 1). The damage is defined as a function of distance to the crack front which rises from 0 to 1 as a distance of $l_c$. The crack front location is determined using a level set function where the iso-zero of this function is the damage front. This definition of damage is used in the constitutive relation of interface elements. The level set function and front location are updated based on the computed crack growth rate with Paris law:

$$\frac{da}{dN} = C\left(\frac{\Delta G}{G_c}\right)^m \tag{1}$$

where $da/dN$ is the crack growth rate, $G_c$ is the fracture energy, and $\Delta G$ is the cyclic variation of energy release rate. The material parameters $C$ and $m$ must be determined experimentally. An accurate computation of energy release rate is the main issue in implementing the Paris law. The TLS method provides an accurate non-local method for computation of the energy release rate by integrating local values of the driving force inside the damaged band. In the proposed discontinuous version of the TLS the local driving force is defined as a function of displacement jump[11].

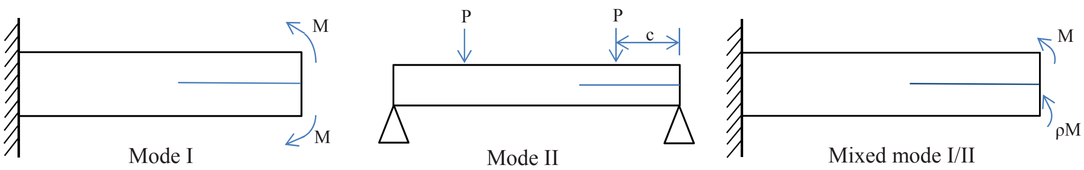


**Figure 2.** Loading conditions in three different fracture modes

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## 3. Results and discussion

The proposed model has been validated under mode I, mode II and mixed-mode loading cases. For this purpose the DCB, 4ENF and mixed-mode test cases (see Fig. 2) have been simulated and the obtained results are compared with experimental data as well as theoretical Paris law. The boundary conditions for these simulations are presented in Fig. 2 which provide a constant crack growth rate under cyclic loading. In these simulations a load ratio ($R$) equal to 0.1 is considered, and a load envelope strategy is used which means that instead of the complete cyclic load a constant load equal to the maximum value of the cyclic boundary conditions is applied. The simulated specimen in all simulations is 150 mm long, 20 mm wide with two arms of 1.5 mm thick with an initial crack of 35 mm. The material properties used for the simulations are related to carbon/epoxy HTA/6376C obtained from [1, 12]. 3D wedge elements connected with 6-node interface elements are used. Furthermore, a conforming 2D mesh is defined on the interface for definition of the level set field. A value of $l_c$ = 5 mm was considered and the smallest size of the finite elements in the 2D mesh at the interface was 0.618 mm. Figures 3, 4 and 5 compare the results obtained from the thick level set model with experimental data and the Paris relation. In these figures, the energy release rate along the horizontal axis is computed from the applied load with beam theory. The crack growth rate along the vertical axis is the averaged crack growth rate measured in the simulation at the side of the specimen. An excellent agreement is observed between the results which demonstrates the accuracy of obtained crack growth rate and computed energy release rate using the thick level set interface model. It is illustrated in figure 5 that the thick level set interface approach does not only allow accurate computation of the energy release rate, but also accurate decomposition of this quantity into the three pure-mode contributions.

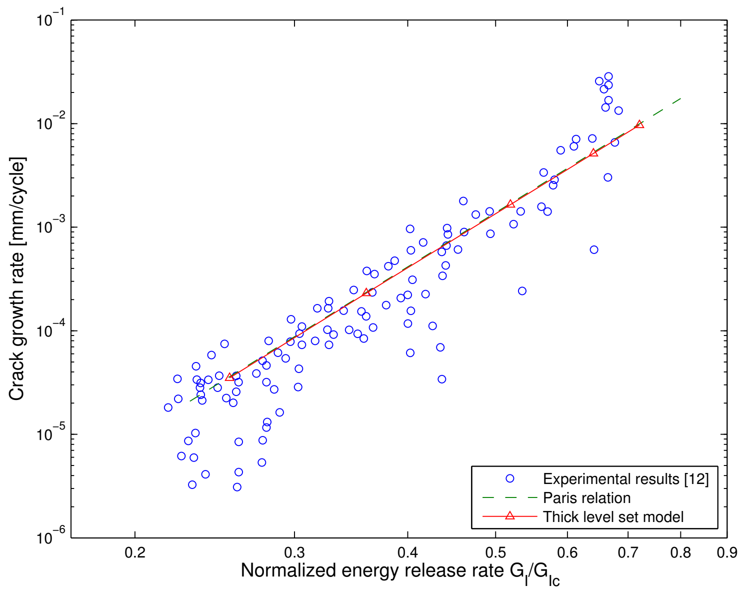


**Figure 3.** Comparison of crack growth rate from thick level set model with experimental data and Paris relation for DCB tests

## 4. Conclusion

An interface thick level set model is introduced and validated in this paper. A new definition of damage is used in the constitutive relation of interface elements. Unlike common fatigue cohesive models which



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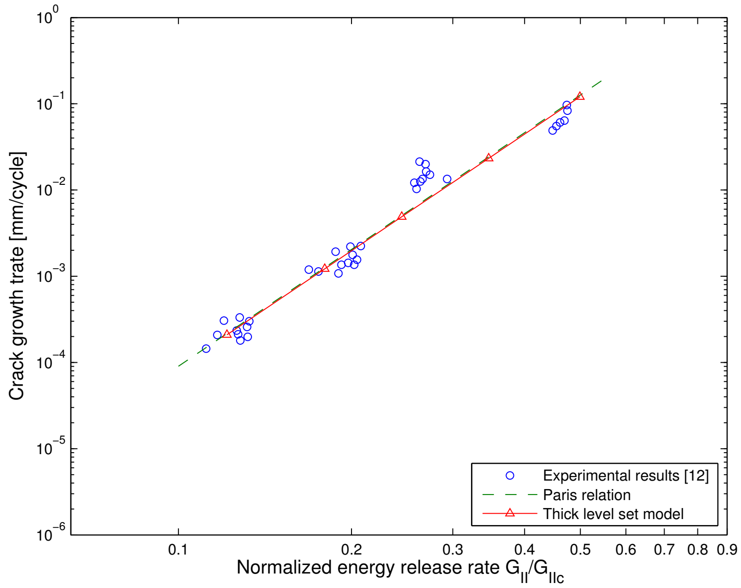


**Figure 4.** Comparison of crack growth rate from thick level set model with experimental data and Paris relation for 4ENF tests

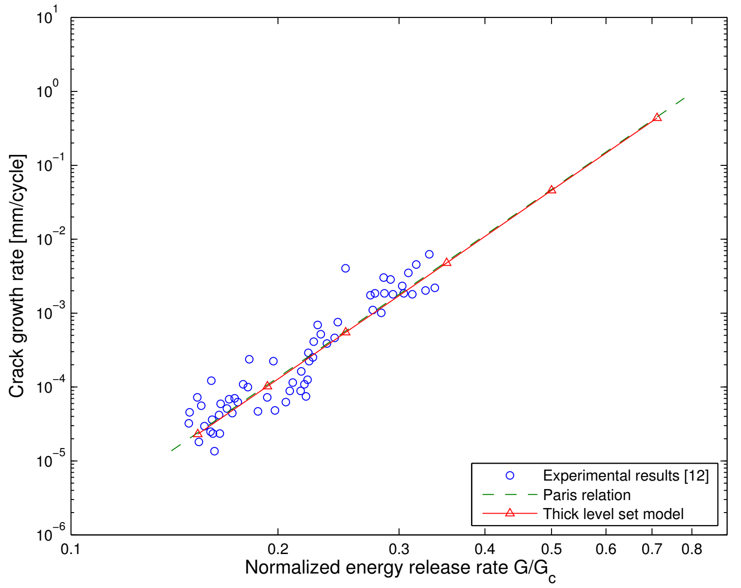


**Figure 5.** Comparison of crack growth rate from thick level set model with experimental data and Paris relation for mixed-mode tests

extract the energy release rate from the cohesive law, the energy is computed non-locally based on the thick level set approach. The comparison between propagation rates in mode I, mode II and mixed-mode simulations with the Paris law demonstrates the accuracy of the proposed model.

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