Modelling Mode I Crack Initiation In Composites Under Fatigue Loading Using Interface Elements

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ABSTRACT

A new method for modelling crack initiation under fatigue loading using cohesive zone interface elements is proposed. The model allows for the formation and growth of a macroscopic crack under low levels of applied load without the presence of an initial crack. This is realised by reducing the maximum stress of the traction-displacement curve as a function of cycles. The energy required for the deterioration of the material is accounted for using the 'equivalent energy approach'. A numerical initiation threshold has been introduced to avoid premature initiation. The interface element is implemented in the explicit finite element code LS-DYNA. Model calibration is carried out using data from three point bend tests on 90° laminates. The model has been applied to predict the onset of matrix cracking in cross-ply laminates under tension-tension fatigue.

1. INTRODUCTION

Delamination in fibre reinforced composite materials has classically been modelled using linear elastic fracture mechanics (LEFM).Various LEFM approaches are used to calculate energy release rate G, for example the J-integral [1], virtual crack extension method [2] and the virtual crack closure technique (VCCT)[3]. These methods give good predictions for the crack growth in composite materials. However, direct application of LEFM in finite element codes requires the existence of an initial crack that can be propagated. Recently, another technique to simulate delamination in composites has been developed using interface elements based on cohesive zone models [4-6]. These interface elements are implemented into finite element (FE) models at potential crack paths and their failure predicts the propagation of delaminations. This allows a crack to advance without complex remeshing algorithms. If appropriate criteria are chosen it is also possible to initiate a crack without initial flaws. The underlying Cohesive Zone Model (CZM) assumes a zone ahead of the crack tip where stresses σ are non-zero and relative displacements u can occur. The failure criterion is introduced in the form of a traction-displacement curve as shown in Fig. 1.

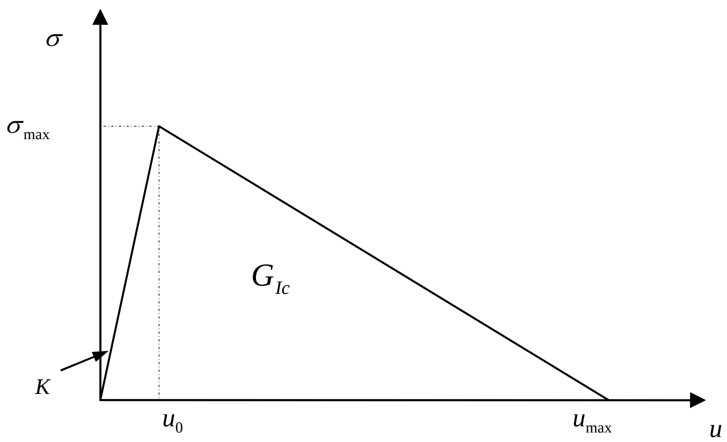


Figure 1: Typical traction displacement curve

When the maximum stress is reached, the interface element undergoes a softening process until the critical fracture energy has been dissipated. Recently, the applications of interface elements have been extended to high-cycle fatigue (HCF) loading using Paris-law based fracture criteria [7-9]. Although the results obtained from these models are in reasonable agreement with experimental observations, an initial crack must be present before the technique can be applied. If the finite element mesh is too coarse to correctly predict the stress concentration at the crack tip or the applied stress is very low, the interface element does not exceed the maximum stress on the traction-displacement curve. In this case, no damage occurs in the element and a crack cannot be propagated. This paper presents a method to overcome these problems by introducing a crack initiation law, hence allowing a total fatigue life model to be formed.

2. FATIGUE MODEL

2.1. General approach

Fatigue life of structures is usually visualised in SN-curves by plotting the numbers of cycles until failure versus the applied maximum stress. On a semi-logarithmic scale, these SN-curves can be approximated by straight lines and be expressed as follows

$$\sigma(N) = \sigma_{\max,static} - const \cdot \log(N) \qquad (1)$$

Where σ, *N*, *const* and *log* are stress, number of cycles, a constant and the logarithm function respectively.

O'Brien et al. [10] have characterised the transverse tension fatigue behaviour of 90° laminates under bending loads using two composite materials - IM7/8552 carbon/epoxy and S2/8552 glass/epoxy. Both materials have been tested under three and four-point bending loads. Transverse cracks initiate at the tensile back face of the beam as illustrated in Fig. 2. This initiation is easy to detect as it can be observed visually due to the almost instantaneous propagation and catastrophic failure of the specimen.

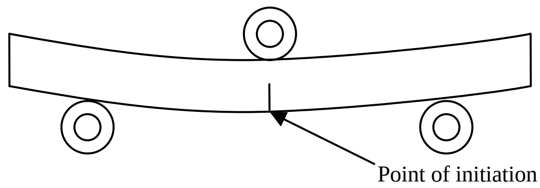


Figure 2: Bending of 90° laminate

It has been observed that the SN-curves obtained by O'Brien for both materials tested can be collapsed into a single SN-curve by normalising with respect to the static failure stress. This indicates that the initiation of damage is solely dependant on the properties of the matrix as both composites contain the same resin system, but differ in the embedded fibre type. Additionally it was found that the normalised SN-curves for both test configurations collapse into a single SN-curve indicating that the slope of the normalised SN-curve is independent of the test configuration. These initiation SN-curves can thus be used to reduce the maximum stress in the traction-displacement curve of the interface elements as a function of cycles. Once the maximum stress is equal to the applied stress in the interface element, the initiation criterion is met and Paris-curve based propagation laws are activated:-,

$$\sigma_{appl} \geq \sigma_{\max} \qquad (2)$$

where σ_{appl} is the stress applied to the interface element and $\sigma_{\max}$ is the maximum stress assigned to the interface element.

The model has been implemented into the explicit finite element code LS-DYNA. The implementation is illustrated in the following flowchart (see Fig. 3)

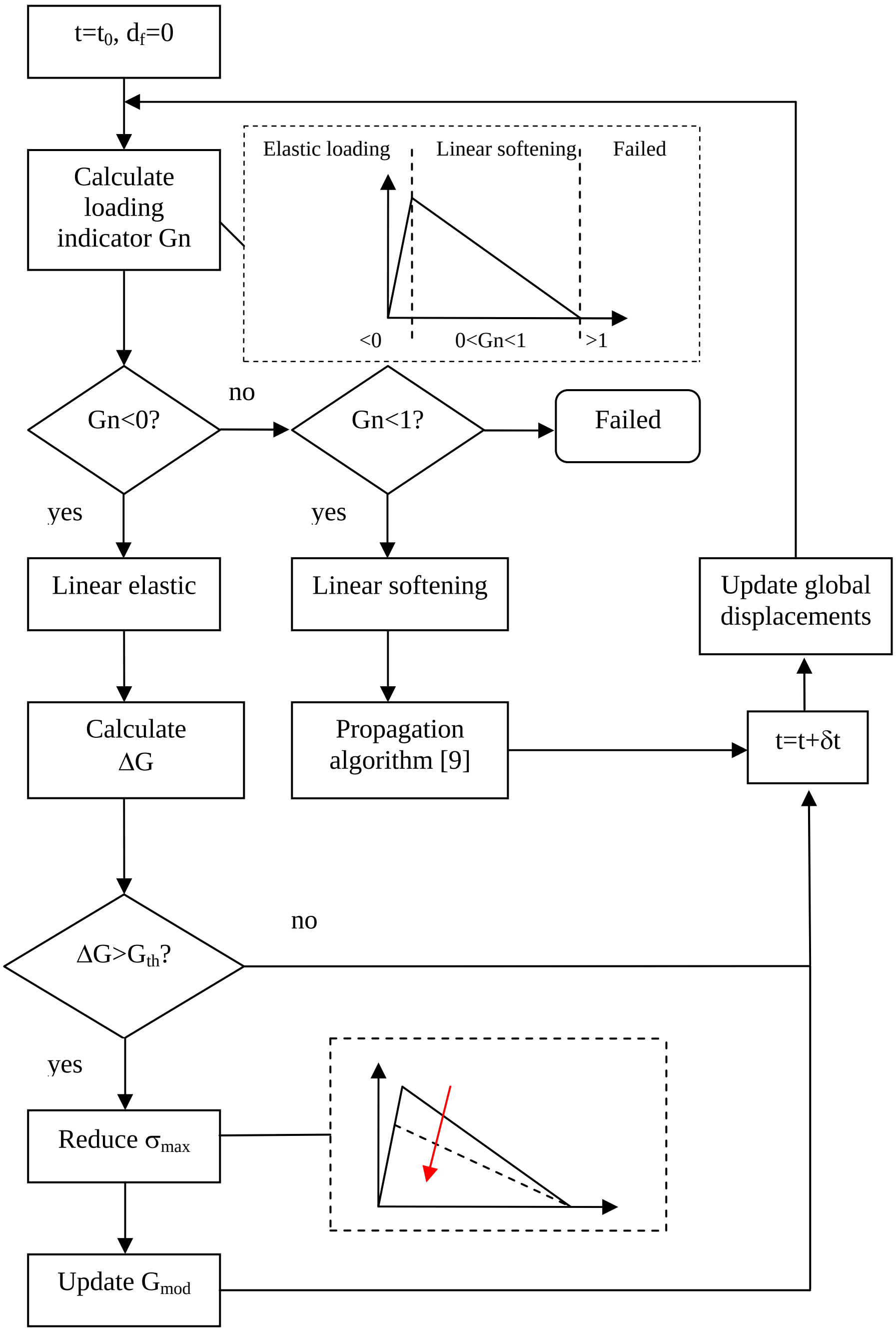
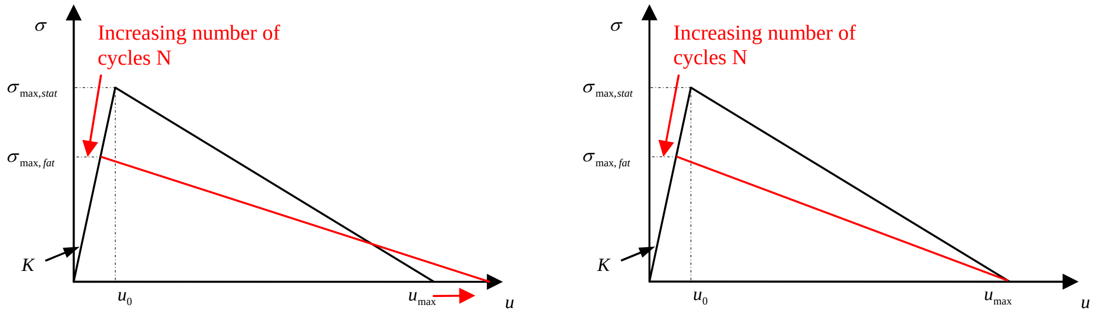


Figure 3: Flow chart of fatigue model

2.2. Initiation laws

As explained in the previous section, to initiate a crack the maximum stress of the traction-displacement curve assigned to the interface element is reduced as a function of cycles. Two different methods for this have been assessed. The first keeps the critical strain energy release rate, G_{Ic}, constant resulting in an increase of the displacement at failure u_{max} as shown in Fig. 4(a). This method has a key flaw in that under very low load levels the maximum displacement increases significantly and eventually prevents the element from failing. The second method takes into account damage accumulation during the initiation process as shown in Fig. 4(b).



(a) Constant critical strain energy release rate (b) Constant maximum displacement

Figure 4: Modified traction-displacement curve

The damage induced during the initiation phase can be explained by the physical deterioration that occurs in the material prior to propagation of the crack. If the traction displacement curve shown in Fig. 4(b) is used then the damage accumulation is somewhat arbitrary and at low load levels there can still be a significant displacement to be achieved once the element has initiated failure. To better account for the deterioration process the ‘equivalent energy approach’ is introduced.

Each stress state in the elastic regime can be assigned an equivalent stress state on the softening curve. The amount of energy needed to reach this equivalent stress state is called “equivalent energy” and is represented by the shaded area in the Fig. 5. The remaining area under the traction-displacement curve is the amount of energy required to fully fail the interface element which results in a revised calculation of $u_{\max}$ to achieve complete failure.

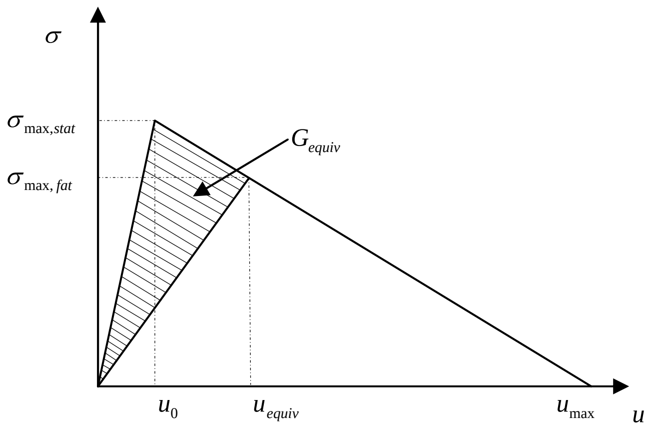


Figure 5: Equivalent energy approach

The equivalent energy can be calculated as follows

$$G_{equiv} = G - \frac{1}{2} \cdot u_{\max} \cdot \sigma_{\max, fat} \,. \tag{3}$$

The remaining energy required to fail the element is then calculated as

$$G_{\mathrm{mod}} = \frac{1}{2} \cdot u_{\max} \cdot \sigma_{\max, fat} \,. \tag{4}$$

The modified energy, G_{mod}, is then used to calculate the crack propagation rate.

2.3. Numerical initiation threshold

Potential problems are encountered with the introduction of this initiation method. For a given loading the algorithm will start to reduce σ_{max} at all locations within a model. This can result in initiation in incorrect locations in complex 3D geometries and initiation at very low stress levels where experimental work does not show any evidence of cracking in the sample. To overcome this a numerical initiation threshold has been introduced. This threshold prevents unwanted initiation at low levels of stress. O'Brien et. al have investigated fatigue thresholds for composites [11] and proposed an energy based linear criterion for delamination onset under cyclic loading:

$$\frac{G_I}{G_{Ith}} + \frac{G_{II}}{G_{IIth}} = 1. \tag{5}$$

To be consistent with the propagation laws implemented in the interface element presented here [9] it is assumed that the driving factor for damage accumulation is the difference between the maximum and minimum energy, ΔG, rather than the maximum energy, $G_{\max}$.

$$\Delta G = G_{\max} - G_{\min} \tag{6}$$

Based on this assumption a similar criterion to equation (5) is proposed

$$\frac{\Delta G_I}{\Delta G_{Ith}} + \frac{\Delta G_{II}}{\Delta G_{IIth}} = 1 \tag{7}$$

And for pure mode I loading,

$$\frac{\Delta G_I}{\Delta G_{Ith}} = 1. \tag{8}$$

Values for ΔG can be obtained from the traction displacement curve as shown in Fig. 6.

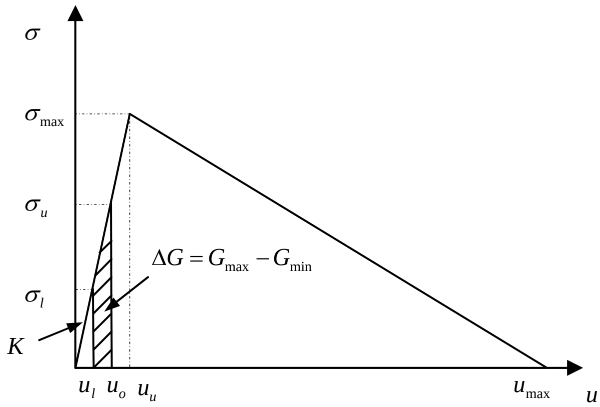


Figure 6: Obtaining delta G from traction-displacement curves

The maximum stress in each load cycle can be expressed as

$$\sigma_u = u_u \cdot K \tag{9}$$

Consequently the minimum stress in each load cycle is dependant on the R-ratio

$$\sigma_l = \sigma_u \cdot R \tag{10}$$

Using simple geometric manipulations it can be shown that

$$\Delta G = \frac{1}{2} \cdot K \cdot u^2 \cdot \left(1 - R^2\right) \tag{11}$$

For constant R and a single mode ΔG can be plotted against u as shown in Fig. 7.

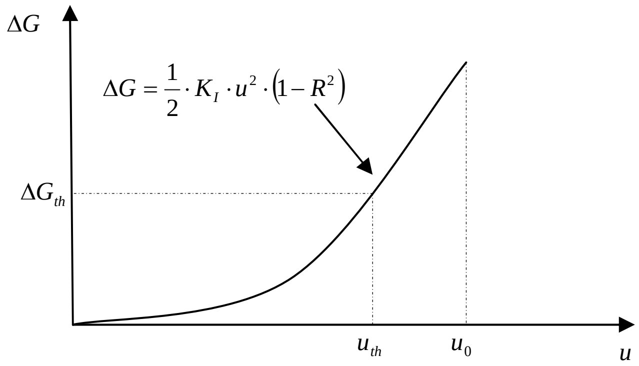


Figure 7: Delta G vs u

2.4. Propagation laws

The initiation laws have been embedded into the existing fatigue damage propagation environment developed by Harper and Hallett [9]. The crack propagation model uses a Paris type law expressed in the form:

$$\frac{\partial a}{\partial N} = C\left(\frac{\Delta G}{G_C}\right)^m \tag{12}$$

Where ∂a/∂N is the crack growth rate and C and m are empirically derived parameters. The cycle frequency (∂N/∂t) can be expressed as cycles per second using a pseudo time step in LS-Dyna allowing the crack propagation rate (∂a/∂N), expressed in terms of distance per cycle, to be converted to distance per unit of pseudo-time (∂a/∂t).

$$\frac{\partial a}{\partial t} = \frac{\partial a}{\partial N}\frac{\partial N}{\partial t} \tag{13}$$

For high-cycle fatigue, ∂N/∂t generally needs to be set to between 1000 and 10,000 in order to achieve measurable crack growth rates without excessive model run-times. A similar cycle jump strategy has been applied to the initiation laws.

A fatigue damage parameter d_f has been introduced and is added to the static damage parameter d_s to calculate the total damage in the interface element D_{tot}.

$$D_{tot} = d_s + d_f \tag{14}$$

The fatigue damage parameter is updated after each time step

$$d_{f,new} = d_{f,old} + \delta N \frac{\partial d_f}{\partial N} \tag{15}$$

The stress components are updated accordingly. A detailed description of the model can be found in [9].

3. MODEL CALIBRATION

Generally, it is problematic to detect moment of damage initiation and most standard tests feature an artificial pre-crack Therefore, damage is already initiated before the test begins. O'Brien and co-workers have carried out a series of three-point-bending tests on 90° laminates which fail instantaneously when a transverse crack initiates at the back face of the beam [10]. In this case, initiation and final failure can be regarded as occurring simultaneously and therefore initiation is visually detectable. SN-data for IM7/8552 glass/epoxy have been taken from [10] and normalised by the static value in order to calibrate the model. A linear SN-curve was then fit through the experimental data as shown in Fig. 8.

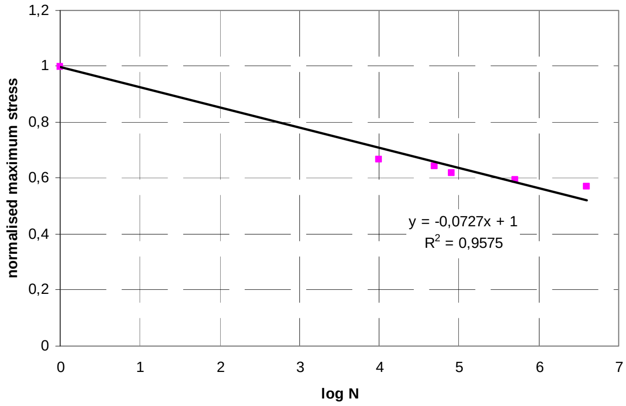


Figure 8: Calibration curve

4. FINITE ELEMENT ANALYSES

4.1. Model setup

Damage development in cross-ply laminates under tension-tension fatigue can be divided into three stages: Matrix cracking in the 90° plies, local delaminations initiating from the matrix crack tips and large-scale delaminations. The first of these damage mechanisms is caused by pure mode I loading.

Matrix cracking of a IM7/8552 carbon epoxy with a $[0,90]_s$ stacking sequence has therefore been chosen as a demonstrator case for the functionality of the initiation method. A unit cell model of this configuration has been set up as shown in Fig. 9. Constant stress solid elements with orthotropic-elastic and thermal properties were used to model the laminate. Each 0° ply has been modelled with one element through the thickness. 90° degree plies have been modelled using two elements through the thickness. The matrix crack has been embedded into the model using a set of thin solid interface elements (t = 0.01mm).

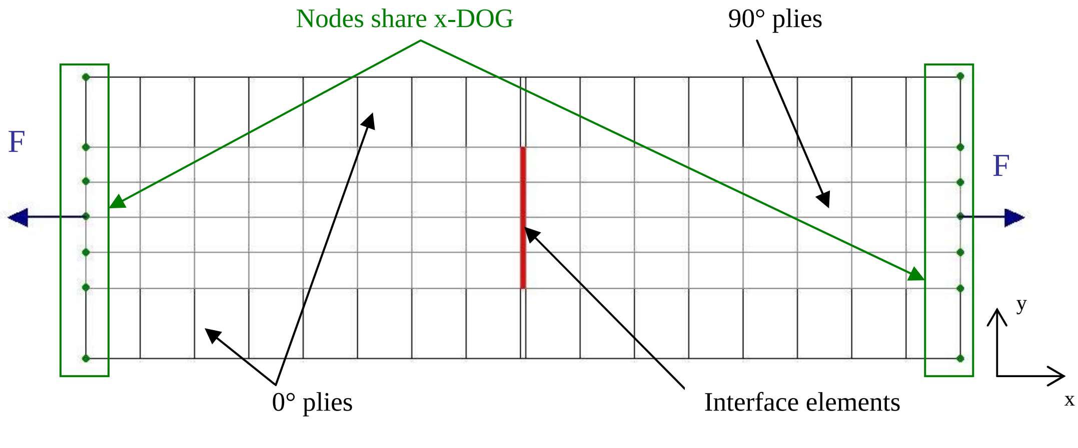


Figure 9: Model Setup

The composite and interface element properties are listed in **Table 1**.

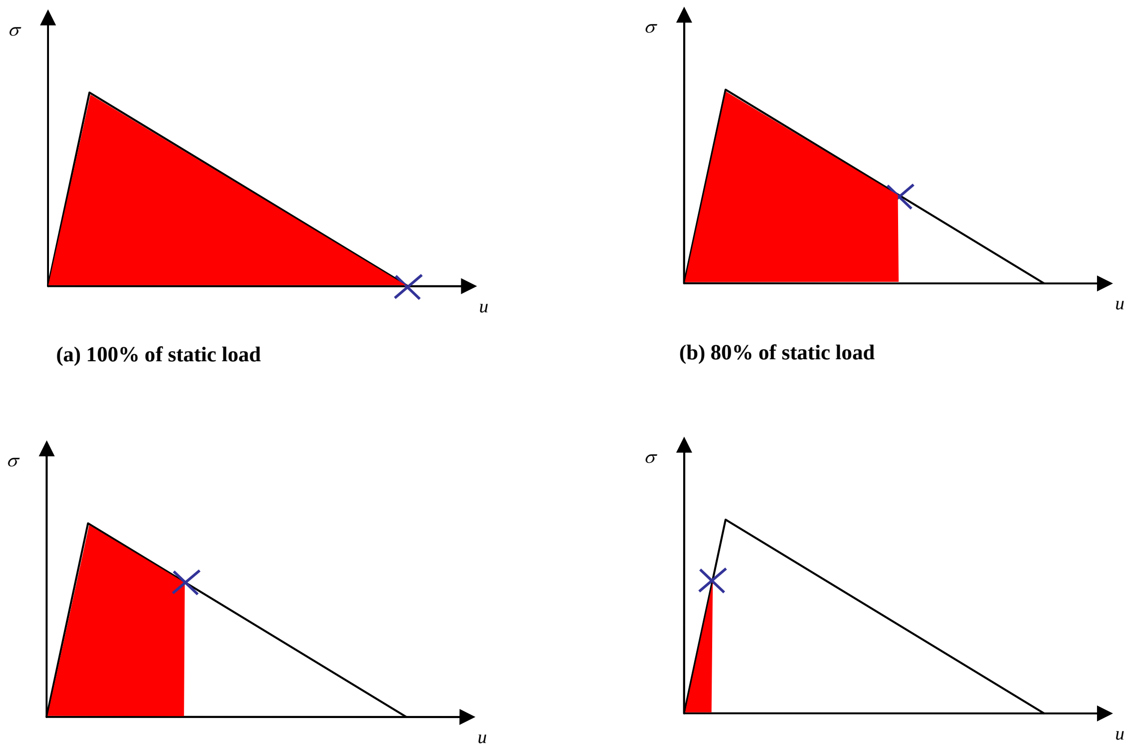
Table 1: Material properties for IM7/8552 carbon/epoxy [4,12]

E_{11} (GPa)	E_{22}=E_{33} (GPa)	G_{12}=G_{31} (GPa)	G_{23} (GPa)	ν_{21}= ν_{31}	ν_{32}
161	11.4	5.17	3.98	0.022619	0.436
G_{Ic} (kJ/m²)	σ_{max} (MPa)	K (N/mm³)	d σ_{max} /dN	C	m
0.26	60	10^5	-0.07	0.0616	5.4

Before the model was mechanically loaded, a thermal load was applied to account for residual stresses resulting from the manufacturing process. The model was then loaded statically to obtain the stress for the physical initiation of a matrix crack. Physical initiation of the crack was defined as the moment when the first interface element completely fails. The numerical initiation occurs when the maximum stress of the interface is reached.
Once the static stress for the initiation of matrix cracking was established, fatigue simulations were carried out on several load levels below the static value (90%, 80%, 70%, 60%, 50%, 40%, 30%). A cycle-jump strategy was applied to obtain reasonable run-times for the fine meshes. Every second of pseudo-time in LS-DYNA corresponds to 10,000 load cycles.

4.2. Results

The simulation results show that the proposed model is capable of initiating matrix cracks at various levels of applied stress. The analyses have shown that in this particular configuration the initiation laws are not required for all levels of fatigue load. Local stress concentrations at the location of potential matrix cracks numerically initiate the damage accumulation in the interface elements as shown in Fig. 10. It is sufficient to apply Paris based crack propagation criteria to fail these elements and propagate a crack.



(a) 100% of static load

(b) 80% of static load

(c) 60% of static load

(d) 40% of static load

Figure 10: Loading indicator on traction-displacement curve

There appears to be a transition for fatigue stresses below a value of about 50% of the static load. Below this transition threshold the interface elements are loaded linear elastically and the unmodified interface element model cannot accumulate damage. The new method reduces the maximum stress of the interface element successfully to allow initiation and subsequent propagation of damage as shown in Fig. 11 for case of fatigue load at 40% of the static case.

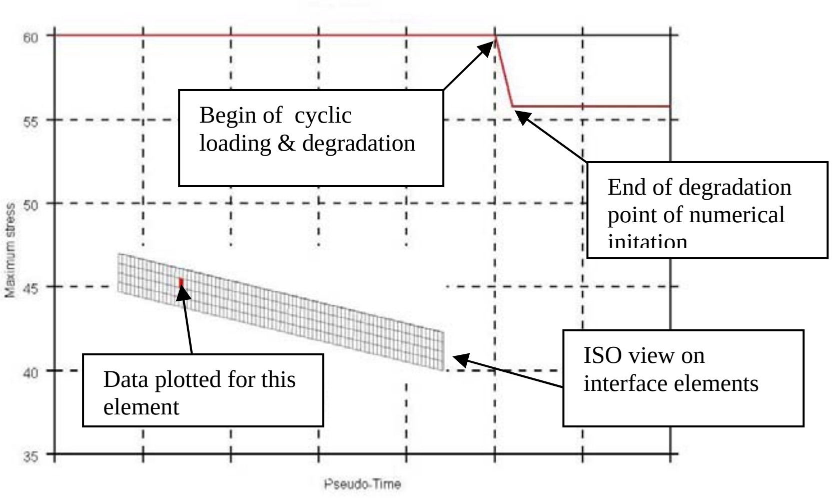


Figure 11: Reduction of maximum stress in traction-displacement curve

The model also accounts for the energy used in the deterioration process of the material. Consequently, the energy needed to fail the interface element is reduced as shown in Fig.12.

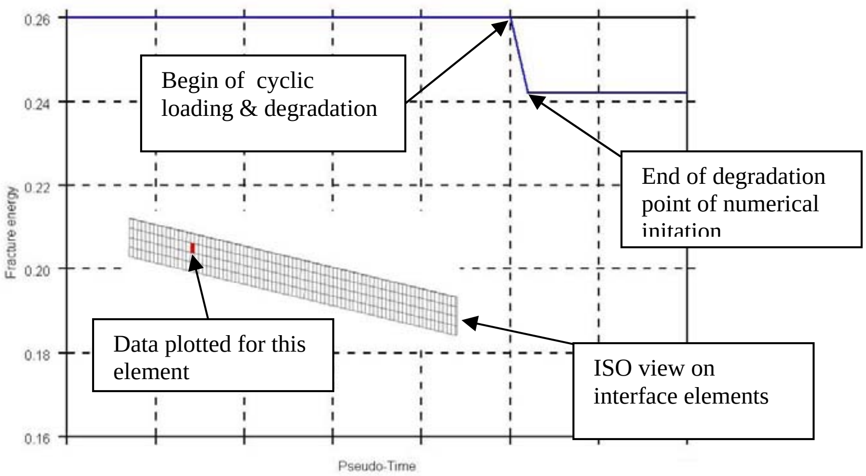


Figure 12: Reduction of fracture energy passed to Paris-subroutine

Figure 13 shows a typical development of the matrix crack across the width. Light grey colour indicates that the interface element has not failed yet while failed elements are shaded in dark grey.

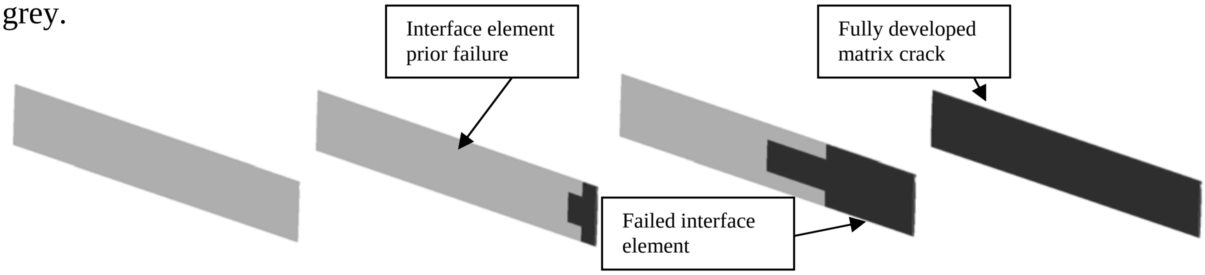


Figure 13: Typical development of matrix crack in cross-ply laminates

It can be seen that the cracks initiate at the edges of the sample and propagate quickly through the width which is in agreement with known experimental observations.

5. CONCLUSIONS AND FURTHER WORK

The predictive capabilities of existing fatigue models using interface elements are limited to cases where local stress concentrations have already caused numerical initiation. The newly developed method reduces the maximum stress of the interface element following an SN-curve for initiation obtained from three-point bending tests on 90° laminates. This process allows initiation of fatigue damage at low levels of stress. The model has proven to work successfully for the initiation of matrix cracking in cross-ply laminates loaded in tension-tension fatigue. Initial results look promising and future work will address the following:

i) Experimental validation of predicted number of cycles until onset of damage
ii) Investigation of mesh-size effects

Work is also underway to extend the predictive capabilities to mode II and mixed mode load conditions.

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