

SIMULATION OF 3D FATIGUE DEBONDING/DELAMINATION IN COMPOSITES USING COHESIVE ZONE

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Abstract

The cohesive zone model has been widely used for the description of quasi-static crack growth of interfaces and recently evolutions have been proposed in order to account for fatigue phenomena. In this work the cohesive zone model previously developed by the authors to simulate fatigue crack growth at interfaces in 2D geometries is extended to 3D cracks under mode I loading.

1 Introduction

Composite materials and structural adhesive bonding showed their first applications in the aerospace industry, but thanks to continuous performance improvement and cost reduction, many more industry fields are approaching the use this type of materials. The extensive employment of composites requires a more and more sophisticated capability to simulate and predict their mechanical behaviour. For this purpose, analytical methods are being progressively integrated or replaced by the Finite Element Method. In engineering applications, fatigue life is one of the most important design issues and for the previously mentioned materials the fatigue life is related to the initiation and propagation of defects, which produce progressive adhesive debonding or composite material delamination.

This kinds of problem were historically studied using fracture mechanics where the kinetic of a fatigue crack was represented by a Paris-like equation which relates the range of strain energy release rate ΔG , to the crack growth da/dN :

$$\frac{da}{dN} = C\Delta G^m \quad (1)$$

In this simple approach the finite element method can be adopted by creating and running models with different crack lengths. For each analysis the value of the strain energy release rate can be obtained using the contour integral or the virtual crack closure technique (VCCT). Hence the number of cycles can be obtained by manually integrating the crack growth rate computed from the Paris law.

In some finite element softwares, this procedure is integrated in special features (i.e. *Debonding in Abaqus[®]). An alternative way for dealing with fatigue crack growth problems is using a cohesive zone model. This model was initially used to described the plastic zone at the crack tip in thin metallic sheets and later it has been used as a micromechanical model for the simulation of the quasi static crack growth problems, especially in the case of interface

cracks such as delamination in composites and bonded joints [1-4]. The possibility to simulate the growth of a defect without any remeshing requirements and the relatively easy possibility to manipulate the constitutive law of the cohesive elements makes the cohesive zone model attractive also for the fatigue crack growth simulation. In the literature several works deal with this topic: Maiti and Geubelle [5], Roe and Siegmund [6] and Muñoz [7] defined models where the cohesive strength is reduced using appropriate laws and parameters in a cycle by cycle approach. Turon et al [8] proposed instead a model where the calibration of cohesive parameter for cyclic loading is not required since a damage homogenization criterion is used for relating the experimental FCG rate with the damage evolution of the cohesive elements. Moreover a cycle-by-cycle FE analysis is not necessary for the integration of damage rate, which means a significant computational time saving. Using [8] as a reference, but modifying the damage definition, including an automatic strain energy release rate evaluation and introducing different mixed mode criteria for the computation of the fatigue crack growth rate, the authors developed a model able to correctly predict fatigue crack growth at interfaces in two-dimensional geometries [9,10]. In this work, the extension of the model to full 3D cracks undergoing mode I fatigue loading is presented, emphasizing especially the changes done with respect the 2D model.

2 General description of the model

For the sake of brevity, only the most important features of the two-dimensional model are shown (the complete description can be found in the literature [9,10]). A triangular cohesive law is used (see Figure 1) where σ_{max} is the maximum stress, K_0 the initial stiffness and δ_c the critical opening. The fracture energy associated, is the area underling the cohesive law. The damage value D reduces the stiffness per unit area K with respect to the initial one, following the equation

$$K = (1 - D)K_0 \quad (2)$$

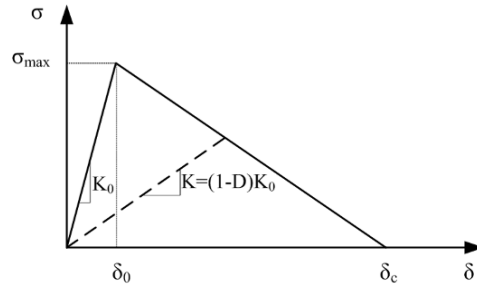


Figure 1. Cohesive law

Damage (D) is representative of the effect of micro void nucleation and micro-cracks, therefore, considering a general Representative Surface Element (RSE) with a nominal surface equal to A_e , and a damaged area due to micro-voids or micro-cracks equal to A_d , D can be written as reported in [11]

$$D = \frac{A_d}{A_e} \quad (3)$$

The damage is increased with the number of cycle using Eq. 4, where A_{CZ} is the process zone extension evaluated directly during the FE analysis (see [9,10] for more detail). Applying the

equivalence criterion between damage and crack growth proposed in [8] the following relationship results:

$$\frac{dD}{dN} = \frac{1}{A_{CZ}} \frac{dA}{dN} = \frac{1}{A_{CZ}} C \Delta G^m \quad (4)$$

This procedure for the prediction of the crack growth rate has been implemented into the FE code ABAQUS using the associated USDFLD subroutine to apply damage to the initial stiffness K_0 . The analysis is carried out by applying a load equal to the maximum load of the fatigue cycle. The strain energy release rate G is computed and therefore, using the cycle load ratio $R=P_{min}/P_{max}$, the strain energy release rate amplitude is calculated as

$$\Delta G = (1 - R^2)G \quad (5)$$

The value of ΔG is compared with the fatigue crack growth threshold ΔG_{th} . If $\Delta G > \Delta G_{th}$ the propagation will take place, otherwise the analysis is stopped and no propagation will occur. In the 2D model, at the beginning of each increment n , the damage D_i^n in the cohesive elements belonging to the process zone A_{CZ} is increased by a given quantity ΔD_i^n . This quantity represents the minimum between the required quantity to reach the unity, and a user-defined value ΔD_{max} . For each element lying in the process zone a variation in the number of cycles, ΔN_i^n is then estimated using Eq. 4 from the knowledge of ΔG^n . The routine searches for the minimum value among the calculated ΔN_i^n . This value, ΔN_{min}^n , is assumed to be the equivalent number of cycles of the increment. Then, the number of cycles is updated (N^{n+1}), and using again Eq. (4) the new damage distribution is computed for all the elements belonging to the process zone (D_i^{n+1}). The process zone is assumed to be where, during the analysis, the opening is higher than the maximum opening shown in the model when the applied strain energy release rate is equal to the strain energy release rate threshold. Since the opening field ahead of the crack tip changes during crack propagation, the process zone dimension is continuously updated.

3 Extension to 3D

For 3D simulation the basic framework of 2D model is maintained although some improvement are required. These and their effect on the result are shown in for a DCB geometry. The model geometry is shown in Figure 2, while the material properties, the applied load, the cohesive law parameters, the specimens dimension and the Paris law equation coefficients are shown in Table 1. The aim is to validate the consistency of the output of the simulation with the values input to the model.

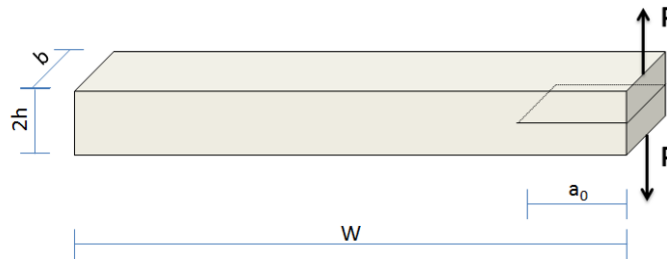


Figure 2. Specimen geometry

Homogenized Young Modulus	E [MPa]	70000
Poisson's ratio	ν	0.25
Applied load	P [N]	100
Cohesive law fracture energy	Γ [N/mm]	1
Cohesive law maximum stress	σ_{max} [MPa]	60
Cohesive law initial stiffness	K_0 [MPa/mm]	14652
Cohesive law critical opening	δ_C [mm]	0.033
Specimen length	W [mm]	50
Specimen width	b [mm]	10
Specimen thickness	2h [mm]	8
Initial crack length	a_0 [mm]	10
Paris law coefficient	C	0.5
Paris law exponent	m	3

Table 1. Material properties

In the two dimensional model the strain energy release rate was computed using two different methodologies: i) using a user defined J-integral formulation and ii) using the energy derivative technique (EDT), based on the general Griffith definition:

$$G = - \frac{d(U - W)}{dA} \quad (6)$$

where U is the strain energy, W the work of external loads and dA is the crack growth increment.

It was demonstrated that for 2D models the EDT methodology is less accurate than the J-integral. But in the case of three dimensional problem the implementation of the J-integral is much more difficult since several paths can be identified along the crack width, and moreover their definition is rather troublesome, especially when dealing with irregular meshes. For these reasons the EDT technique is used in 3D models. In order to overcome the troubles arisen from scatter in the G evaluation, its trend is fitted using a second order polynomial law. Figure 3 shows an example of this fitting.

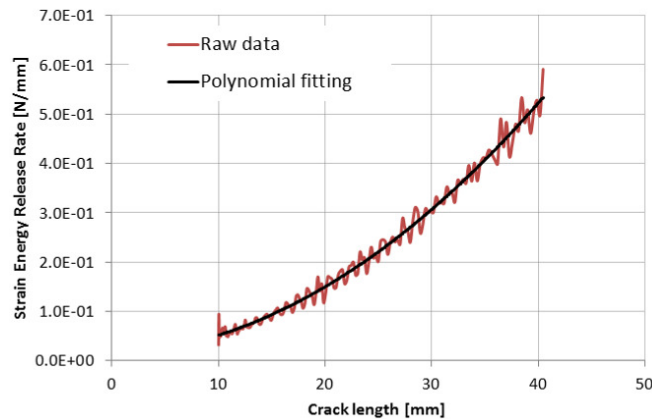


Figure 3. Example of polynomial fitting of the G vs. a trend.

This fitting requires a modification of the procedure since the crack growth rate and the number of cycle cannot be directly computed during the analysis, but they can only be computed at the end of the simulation.

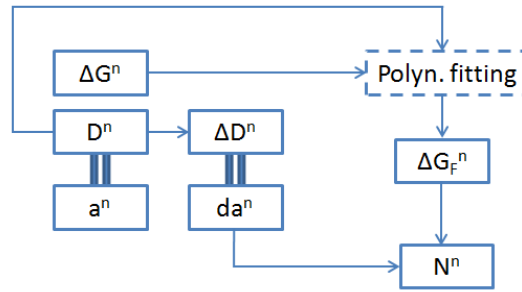


Figure 4. Flow diagram of the modified procedure

The procedure is modified as shown in Fig. 4: for each increment n , the values of ΔG^n , and for each element D_i^n (and the equivalent crack length a^n) and ΔD_i^n (and the equivalent crack length increment da^n) are computed and stored in appropriate arrays. When the analysis is completed the polynomial fitting is carried out using the (ΔG^n) and (a^n) arrays. A new array (ΔG_F^n) containing the fitted value of the strain energy release rate amplitude is therefore created and used in conjunction with the (da^n) array for the calculation of correct the number of cycle (N^n) by using Eq. 4.

Moreover for the calculation of G during the initial monotonic loading and in the first increment of the fatigue simulation, an initial crack increment is required. Therefore the specimens is initially loaded until the maximum load, then the element showing the higher opening is deactivated and finally the specimen is unloaded. The element deactivation produces a artificial crack growth and from the strain energy extrapolated during the loading ad subsequent unloading the strain energy release rate can be computed using Eq. 6.

4 Results

In order to verify the accuracy of the model, the value of G during the initial loading (Fig. 5), the estimation of G during the crack growth (Fig. 6) are compared with reference trend obtained using the VCCT method on an equivalent DCB model. Moreover in Fig. 7 the crack growth rate resulting from the analysis is compared with the reference trend representing Eq. 1 obtained using the values of C and m shown in Table 1.

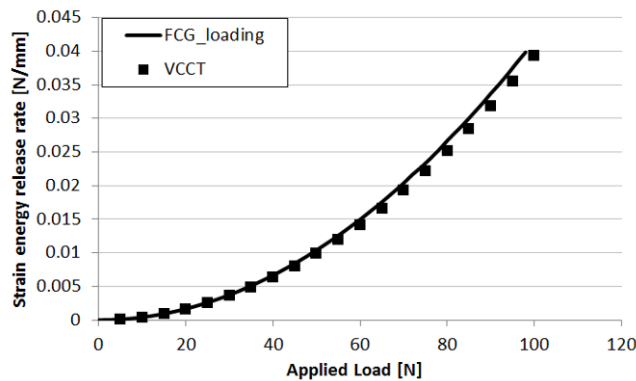


Figure 5. Strain energy release rate during the initial loading. Comparison between result of VCCT and results of the FCG procedure.

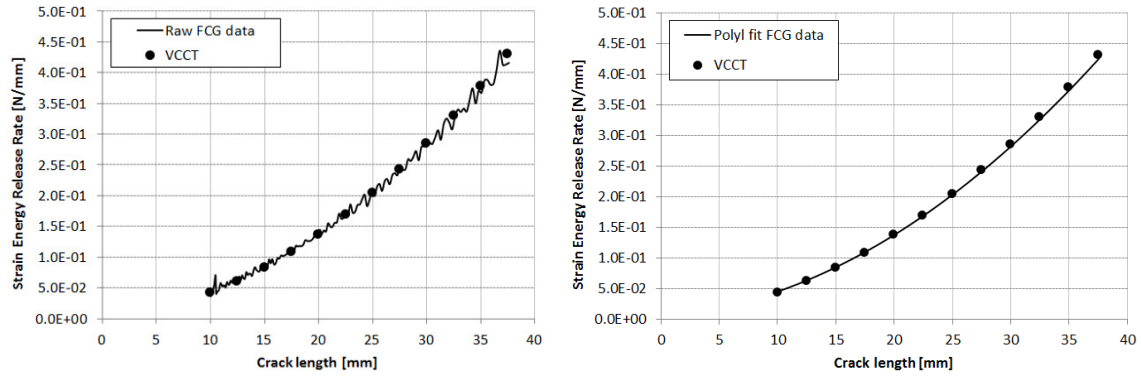


Figure 6. Strain energy release rate during the crack propagation. Comparison between result of VCCT and results of the FCG procedure before and after the polynomial fitting.

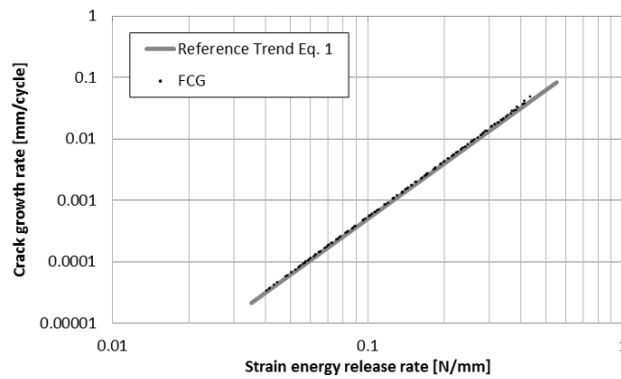
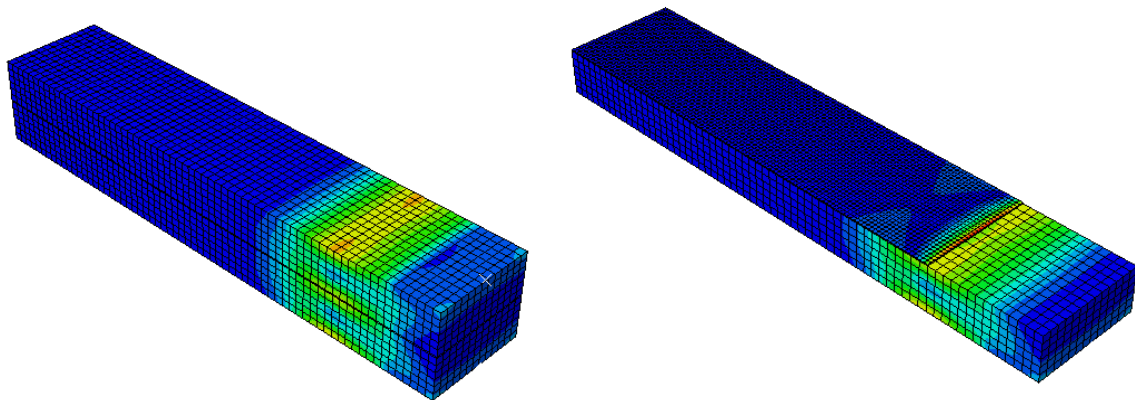


Figure 7. Crack growth rate. Comparison between the reference trend and the results of the FCG procedure.

In general the results of the simulation are in good agreement with the reference trend. Moreover Fig. 6 shows the influence of the polynomial fitting over the crack length vs. strain energy release rate data: it can be noticed that the errors in the estimation of G are reduced, resulting in a better prediction of the number of cycles.



a)

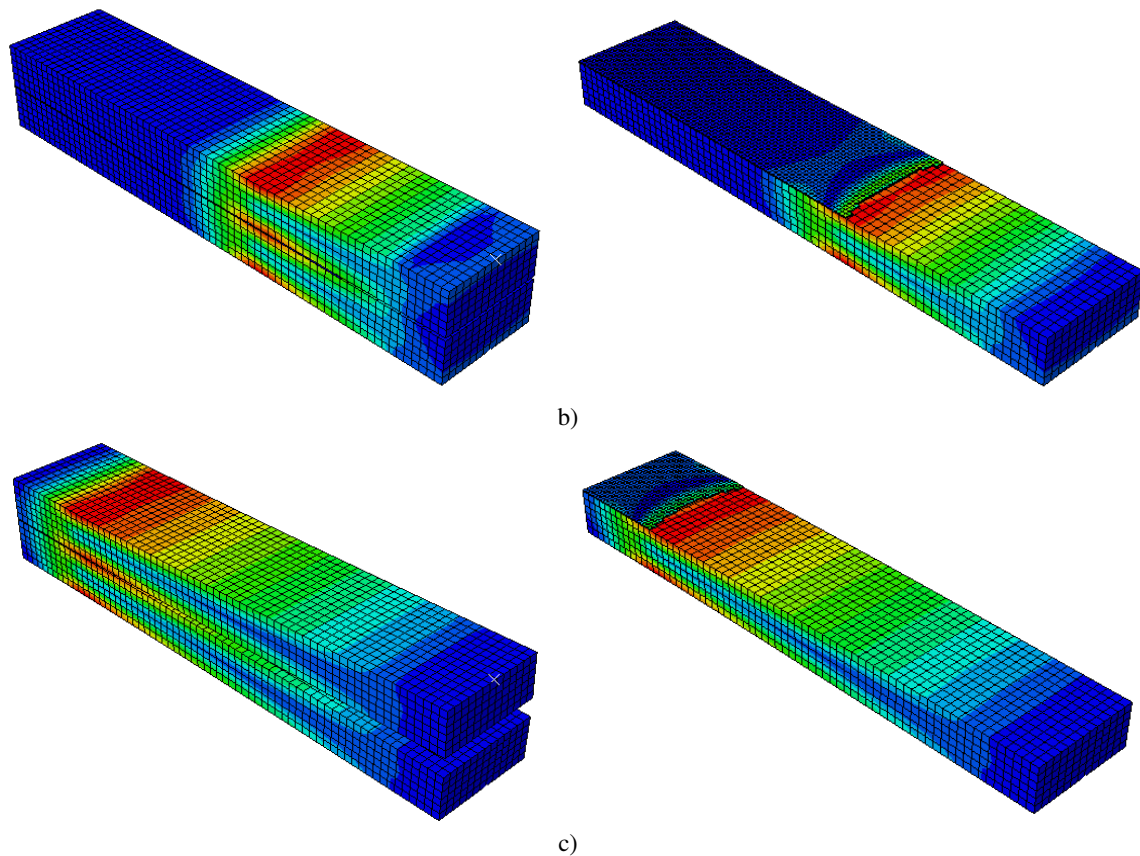


Figure 8. Stress distribution and progressive crack growth (damaged element are removed) during the analysis (a: at the end of the initial loading, b: during the propagation, c: before the final fracture).

Fig. 8 shows the deformed shape of the specimen and the crack front at different stage of propagation. It can be noticed that a slightly bowed crack front shows up, as expected due to the different constraint along the crack front.

5 Conclusions

In this work an initial extension to 3D model of the 2D cohesive zone model, modified in order to account for the fatigue crack growth has been presented. The result are compared whit reference trend (VCCT or analytical) and a good agreement is found.

References

- [1] Barenblatt G., The mathematical theory of equilibrium cracks in brittle fracture. *Advanced Applied Mechanics* **7**, pp. 55-129, (1962).
- [2] Hutchinson J.W., Evans A.G., Mechanics of materials: top-down approaches to fracture, *Acta Materialia*, **48**, pp. 125-135 (2000)
- [3] Blackman. B.R.K., Hadavinia, H., Kinloch, A.J., Williams, J.G. The use of a cohesive zone model to study the fracture of fibre composites and adhesively-bonded joints, *International Journal of Fracture*, **119**, pp. 25-46 (2003)
- [4] Li S., Thouless, M.D., Waas, A.M., Schroeder J.A. and Zavattieri, P.D. Use of Mode-I cohesive-zone models to describe the fracture of an adhesively-bonded polymer-matrix composite. *Composite Science and Technology* **65**, pp. 281-293, (2005)
- [5] Maiti S, Geubelle PH. A cohesive model for fatigue failure of polymers. *Engineering Fracture Mechanics*, **72**, pp. 691-708 (2005)

- [6] Roe KL, Siegmund T. An irreversible cohesive zone model for interface fatigue crack growth simulation. *Engineering Fracture Mechanics*, **70**, pp. 209-232 (2003)
- [7] Muñoz J.J., Galvanetto U., Robinson P., On the numerical simulation of fatigue driven delamination with interface element. *International Journal of Fatigue*, **28**, 1136-1146, (2006)
- [8] Turon A, Costa J, Camanho PP, Dávila CG. Simulation of delamination in composites under high-cycle fatigue. *Composites*, **38**, pp. 2270-2282, (2007)
- [9] Pirondi A., Moroni F. An investigation of fatigue failure prediction of adhesively bonded metal/metal joints, *International Journal of Adhesion & Adhesives*, **29**, pp. 796–805, (2009)
- [10] Pirondi A, Moroni F, Simulating fatigue failure in bonded composite joints using modified cohesive zone model. *Composite joints and connections - Principles, modeling and testing*. Woodhead publishing, Cambridge (2011).