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A cohesive zone model for three-dimensional fatigue debonding/delamination

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Abstract

The cohesive zone model (CZM) has found a wide acceptance as a tool for the simulation of delamination in composites and debonding in bonded joints. Recently, fatigue-devoted implementations of CZM have been proposed. In earlier works, the authors have developed a model of the cohesive zone able to correctly simulate the propagation of fatigue defects in two-dimensional geometry. The procedure has been implemented in the finite element solver (Abaqus) by programming the appropriate software-embedded subroutines. Part of the procedure is devoted to the calculation of the strain energy release rate, G, necessary to know the growth of the defect. The model has been then extended to 3D cracks with quasi-straight crack front, where G could be evaluated by the contour-integral on parallel slices along the crack front. The aim of this work is to extend the cohesive zone model calculation of G using contour integral and the crack front evolution to 3D cracks with non-straight crack front.

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Keywords: fatigue, debonding/delamination; cohesive zone; finite element analysis

1. Main text

Composite and hybrid metal/composite structures are nowadays present not only in the aerospace industry, but thanks to continuous performance improvement and cost reduction, also many more industrial fields are

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approaching the use of multimaterial structural elements. This requires, in turn, extensive use of adhesive bonding and a more and more sophisticated capability to simulate and predict the strength of bonded connections where, for this purpose, analytical methods are being progressively integrated or replaced by Finite Element Analysis (FEA). In engineering applications, it is well established that fatigue is the root cause of many structural failures. In the case of bonded joints, fatigue life is related to the initiation and propagation of defects starting at free edges of joining regions or other features, such as through-thickness holes. In the case of composite or metal/composite joints, fatigue can start also from defects at the same locations cited above, with the difference that the crack may either run into the adhesive or become a delamination crack. Especially in the case of damage tolerant or fail safe design, it is necessary to know how cracks, or in general defects, propagate during the service life of a component. A numerical method able to reproduce three-dimensionally the fatigue debonding in structures is therefore necessary to improve their performances.

The relationship between the applied stress intensity factor and the fatigue crack growth (FCG) rate of a defect is generally expressed as a power law (Paris and Erdogan, 1961). In the case of polymers, adhesives and composites, the relationship is traditionally written as a function of the range of strain energy release rate (ΔG) as

$$\frac{da}{dN} = B\Delta G^{d} \tag{1}$$

where B and d are parameters depending on the material and load mixity ratio, and a is the defect length. In this simple form, the presence of a fatigue crack growth threshold and an upper limit to ΔG for fracture are not represented although, when needed, expressions accounting for these limits, as well as for the influence of the load ratio of the cycle $R=P_{min}/P_{max}$, can be easily found in the literature.

When a theoretical solution for the strain energy release rate does not exist, Finite Element (FE) simulation is commonly used to compute it. The prediction of crack growth can be then carried out by a stepwise analysis, each step corresponding to a user-defined crack growth increment and the number of cycles is obtained by integrating the crack growth rate computed from the Paris law. To speed up the process, in some finite element softwares, this procedure is integrated in special features (for example the *Debonding procedure in Abaqus®, Dassault Systèmes, Paris, France), where the strain energy release rate is obtained using the Virtual Crack Closure Technique (VCCT).

An alternative way for dealing with fatigue crack growth problems is using the cohesive zone model (CZM). This model is commonly adopted for the simulation of quasi static fracture problems, especially in the case of interface cracks such as in bonded joints and delamination in composites. The possibility to simulate the growth of a crack 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 (Turon et al., 2007; Khoramishad et al., 2010; Harper and Hallett, 2010, among others). However, differently from VCCT, three-dimensional fatigue debonding/delamination with CZM is not yet state-of-art in finite element softwares. Using Turon et al. 2007 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 (Moroni and Pirondi, 2012). The model was then extended to 3D planar cracks in Moroni et al. (2013).

The aim of this work is to extend the cohesive zone model calculation of G using contour integral and the crack front evolution to 3D cracks with non-straight crack front.

2. Description of the CZM

2.1. General features

For the sake of brevity, only the most important features of the model are shown (the complete description can be found in Moroni and Pirondi, 2012 and Moroni et al., 2013). 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 corresponds to the area underlying the cohesive law. The damage value D decreases the stiffness per unit area K with respect to the initial one, see Fig. 1.

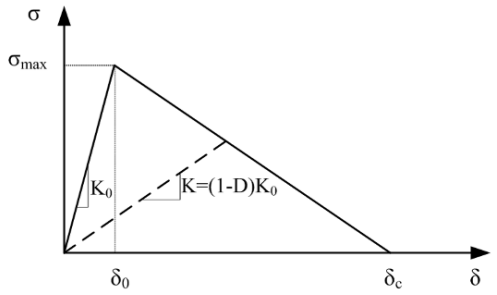


Fig. 1. Cohesive law

Damage 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 (Lemaitre, 1985)

$$D = \frac{A_d}{A_e} \tag{2}$$

Applying the equivalence criterion between damage and crack growth proposed in Turon et al. (2007), damage increases with the number of cycles following Eq. (3), where A_{CZ} is the process zone area, evaluated by FE analysis on-the-run.

$$\frac{dD}{dN} = \frac{1}{A_{CZ}} \frac{dA}{dN} = \frac{1}{A_{CZ}} B \Delta G^d \tag{3}$$

The procedure for the prediction of the crack growth rate has been implemented into the FE code ABAQUS using the embedded USDFLD subroutine to apply damage to the initial stiffness K_0. The simulation is carried out as a static analysis where a load equal to the maximum load of the fatigue cycle is applied. The strain energy release rate G is computed and then, using the cycle load ratio $R=P_{min}/P_{max}$, the strain energy release rate amplitude is calculated as $\Delta G=(1-R^2)*G$. Under mixed-mode I/II loading conditions, the parameters B and d of Eq. (1) are function of mixed mode ratio $MM = G_{II}/(G_I + G_{II})$ according to Kenane and Benzeggagh (1997)

$$d = d_1 + (d_2 - d_1) \cdot (MM)^{m_d} \tag{4}$$

$$\ln B = \ln B_2 + (\ln B_1 - \ln B_2)(1 - MM)^{m_B} \tag{5}$$

where d_1, B_1 and d_2, B_2 are, respectively, the parameters under pure mode I and pure mode II, and m_B and m_d are material parameters. 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. 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 $\Delta D_i^n = \min\{1-D_i^n, \Delta D_{max}\}$ where ΔD_{max} is a user-defined value. For each element lying in the process zone an increment in the number of cycles, ΔN_i^n is then estimated using Eq. (3) and the value of ΔG at that increment, ΔG^n. The routine searches for the minimum value among the calculated ΔN_i^n. This value, $\Delta N_{min}{}^n$, 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. (3) the new damage distribution is computed for all the elements belonging to the process zone (D_i^{n+1}). The process zone is defined as where, during the analysis, the opening is higher than the maximum opening in the cohesive zone 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 area is continuously updated.

2.2. Evaluation of G for 3D planar cracks

The ΔG at each increment is required in order to evaluate the crack growth rate. In 2D, G is evaluated through the calculation of the J-integral along a path Ω corresponding to the top and bottom nodes of the cohesive elements. With this choice, and neglecting geometrical nonlinearity, the J-integral reduces to:

$$G = J = -\int_{\Omega}\left(\sigma_{22}\frac{\partial u_2}{\partial x_1} + \sigma_{12}\frac{\partial u_1}{\partial x_1}\right)d\Gamma \tag{6}$$

Extracting the opening/sliding and the stresses in the cohesive elements at the beginning of the increment, the strain energy release rate is then computed. An interesting feature of this approach is that the mode I and the mode II components of the J-integral can be obtained by integrating separately the second or the first component of the integral in Eq.(6), respectively. For 3D simulation of planar cracks, the calculation of ΔG can be simply done using Eq. (6) on parallel contours along the crack front in width direction, provided the cohesive zone is meshed with a regular grid equally sized brick cohesive elements (Fig. 2). The damage rate dD/dN can be therefore different along the crack front depending on the value of J.

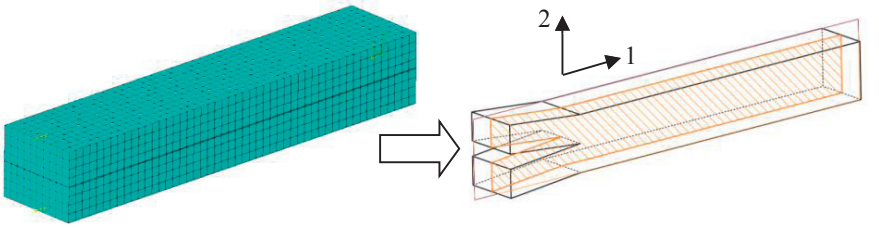


Fig. 2. The 3D geometry is reduced to 2D slices, each one pertaining to a row of cohesive elements.

2.3. Evaluation of G for 3D general cracks

At each increment, the crack front is identified then G is evaluated along every local direction of crack propagation.

The routine looks for integration points having at the same time: i) $D < 1$; ii) at least one surrounding point with D = 1. The segments that separate the points with $D < 1$ from the points with $D = 1$ define the crack front and the direction of propagation $\boldsymbol{n}$, Fig. 3(b). At every point of the front, G is evaluated through the J-integral (Eq.(6), where also local Mode III can be taken into account) along the direction of propagation. Once $\Delta N_{min}{}^{n}$ is computed (see Sect. 2.2), the increment of damage at each point of the front is evaluated by using Eq. (3).

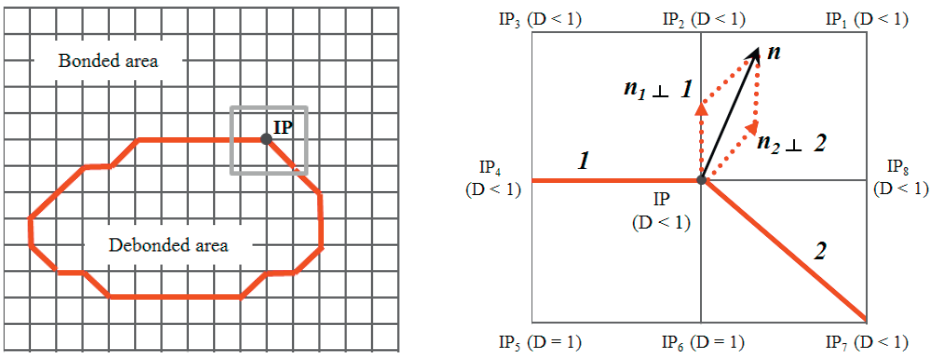
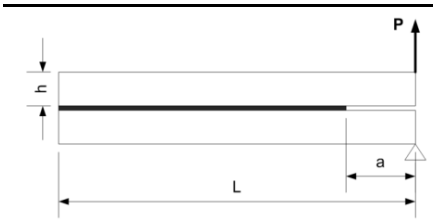


Fig. 3. (a) Crack front of generic shape; (b) Identification of local crack front at integration point IP.

3. FE model

As the procedure described in Sect. 2.3 has been implmented so far only for Mode I, the FE model represents a Double Cantilever Beam (DCB) geometry, Fig. 3. The material properties, cohesive law parameters and Paris law equation coefficients are given in Table 1.



L [mm]	165
b [mm]	20
2h [mm]	10
a_0 [mm]	20
P [N]	300

Fig 4. DCB geometry.

The mesh size in the adherends is 1mm, while in the cohesive layer it is reduced to 0.5mm. A load ratio R = 0 is assumed.

Table 1. Material properties [8,12]

Young's Modulus	E [MPa]	70000
Poisson's ratio	ν	0.3
Mode I Cohesive energy	Γ_I [N/mm]	0.26
Mode I Cohesive strength	σ_{max} [MPa]	30
Initial stiffness of cohesive law	K_0 [MPa/mm]	10000
Paris law coefficient	B	0.0616
Paris law exponent	d	5.4

4. Results

The first ten millimeters of crack propagation have been simulated. In order to verify the accuracy of this approach, the strain energy release rate has been compared with the analytical solution (Krenk, 1992). The values of G_I obtained by 3D VCCT and planar cracks 3D CZM (Giuliese et al., 2013) are plotted on the same diagram. As the 3D crack front is slightly bowed, the G_I and crack length are average values. All the sets show quite a good correspondence (Fig. 5 (a)). The crack front during the propagation is shown in Fig. 5 (b). Fully damaged element are colored in red.

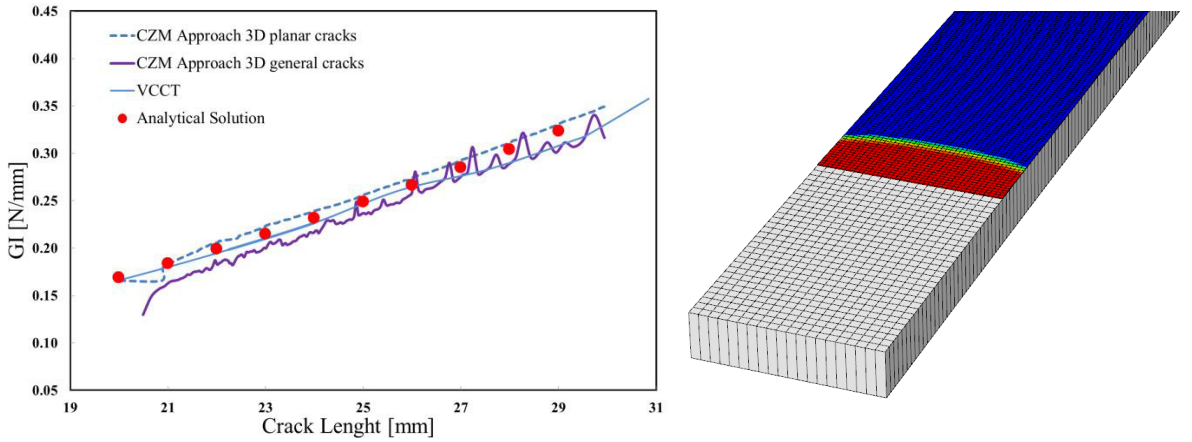


Fig 5. (a) Energy release rate (G_I) versus crack length; (b) Cohesive zone in FE simulation

5. Conclusions

A new procedure for simulating fatigue debonding/delamination with cohesive zone is presented. Unlike the previous approach (Moroni et al., 2013), propagation of arbitrarily shaped cracks can be simulated (Fig. 6). Regular hexahedral meshes in cohesive zone are needed. So far this approach has been tested on a DCB geometry; G_I trend has shown a very good agreement with analytical solutions and previous FEA analysis.

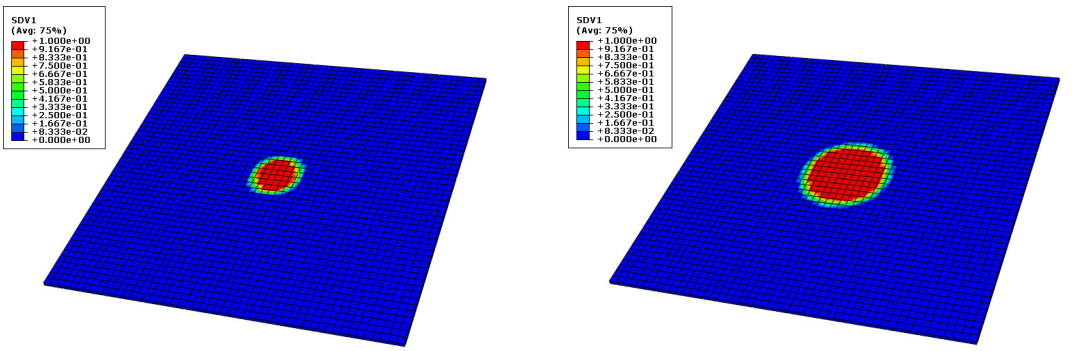


Fig 6. A penny-shaped crack propagation

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