Through-Thickness Element Splitting for Simulation of Delamination in Laminated Composite Materials

Ofir Shor and Reza Vaziri

Composites Group, The University of British Columbia, Vancouver, B.C., Canada

Abstract

A new methodology is presented in this paper that allows simulation of the delamination mode of failure in large-scale composite structures. This is achieved by locally and adaptively splitting the structural shell elements through their thickness, while introducing cohesive zones in regions where delamination is about to take place. The delamination damage can thus propagate in the structure as the simulation progresses. A benchmark mechanical example is solved using this approach and the results are verified against those obtained using other numerical methods.

.

Introduction

The increasing use of laminated composite materials in advanced structural applications requires the ability to predict their behavior under the expected service loads. Laminated composites can generally be described as quasi-brittle materials, with a post-elastic behavior that can be characterized by the degradation of their mechanical properties, due to the progression of various damage mechanisms. The debonding of adjacent laminate layers, also known as delamination, is considered to be one of the most dominant damage mechanisms in the failure of composite laminates. Delamination is often combined with other failure mechanisms, and will usually lead to a reduction in structural stiffness and load carrying capability. Delamination can also lead to instability and premature structural failure under compressive loading. The difficulty of detecting delamination damage in composite structures, and the catastrophic failure that can result from its existence, justify the importance of predicting its influence on the structure's performance, and raises the necessity to predict its initiation and propagation.

Simulating and predicting delamination damage growth in composite materials is a challenging task. Most current research is focused on simulating this damage mode for simple cases, where it can be isolated from the other damage mechanisms in the material. In most real world applications, however, interaction between delamination and the other damage mechanisms is very common. Current numerical models struggle to give reliable results even for simple test cases, as was demonstrated in the recent World-Wide Failure Exercise [1].

There are various numerical approaches aimed at simulating delamination in composite materials. Early methods were based on stress-based criteria, where the inter-laminar and out-of-plane stresses ($\sigma_{13}, \sigma_{23}, \sigma_{33}$) were used to predict the initiation and growth of delamination damage in the material. These models were proven to be effective in capturing the *initiation* of delamination, but could not capture the scale effects as in a fracture-based model [2]. Therefore, it is widely accepted in the scientific community that stress-based methods cannot be used accurately to predict the delamination *propagation* and *growth.*

A well-known method which can be used to simulate delamination crack propagation in composite materials, and is based on fracture-mechanics principles, is the Virtual Crack Closure Technique (VCCT), originally developed by Rybicki et al. [3]. VCCT is a robust method that can be easily implemented in commercial finite element codes, and is based on the assumption that the energy required to propagate a crack of length a by an incremental length Δa is equal to the energy required to close the crack of length $a + \Delta a$ back to its original length a. This required energy is equal to the strain energy release rate, G, hence VCCT is essentially a numerical technique used to calculate G, given the assumption of an *elastic* material. The strain energy release rate can be computed using nodal forces and displacements located at the crack tip's *vicinity*. Once computed, the strain energy release rate can be used to calculate the propagation of the delamination front, by comparing its value to some critical value, G_c, which is considered to be a material property, or some function thereof, $f(G_c)$. An essential requirement for the use of VCCT is the existence of a pre-crack with a finite length embedded in the finite element model. This requirement is due to the fact that the value of the strain energy release rate G vanishes at zero crack length. This limits the use of the VCCT method to cases where the location of the delamination crack, and its growth path, are known and are modeled explicitly prior to the analysis. In addition, since VCCT is based on Linear Elastic Fracture Mechanics, it is limited to cases where the size of the fracture process zone is negligibly small compared to the other structural dimensions. *This assumption is not valid for many quasi-brittle materials*. In such cases, the fracture process zone as well as the embedded cohesive tractions have to be modeled explicitly. Cohesive zone models have been developed over the past decades to address the above issues.

When using the cohesive zone method, the need to calculate the non-physical singular stress field at the crack tip is eliminated by using a force-displacement relation between the nodes in the finite element mesh (*traction-separation law*). This law is the basis for computing the delamination crack initiation, propagation, and opening. The fracture process zone (Figure 1 a), is governed by the relation between the force and the relative displacement of the nodes located at the two opposing crack faces (Figure 1 b), and is monitored at each time step of the analysis. A releasing criterion is implemented, which enables complete node separation and the creation of a new, traction-free surface. Thus, cohesive zone models can deal with the nonlinear zone ahead of the crack tip, due to plasticity or micro-cracking present in many materials, without having the need to finely mesh the crack tip region.

A typical bilinear traction-separation law is shown in Figure 2. As the interface gap λ increases, the traction stress σ increases linearly as well, until a specified displacement λ_0 is reached. At λ_0, the traction achieves its highest magnitude (σ_{max}). From this point on, if the displacement is further increased, the stress drops linearly until a critical value of crack opening, λ_{cr}, is reached at which point the traction reduces to zero. The area under the traction-separation curve is equal to the critical strain energy release rate G_c.

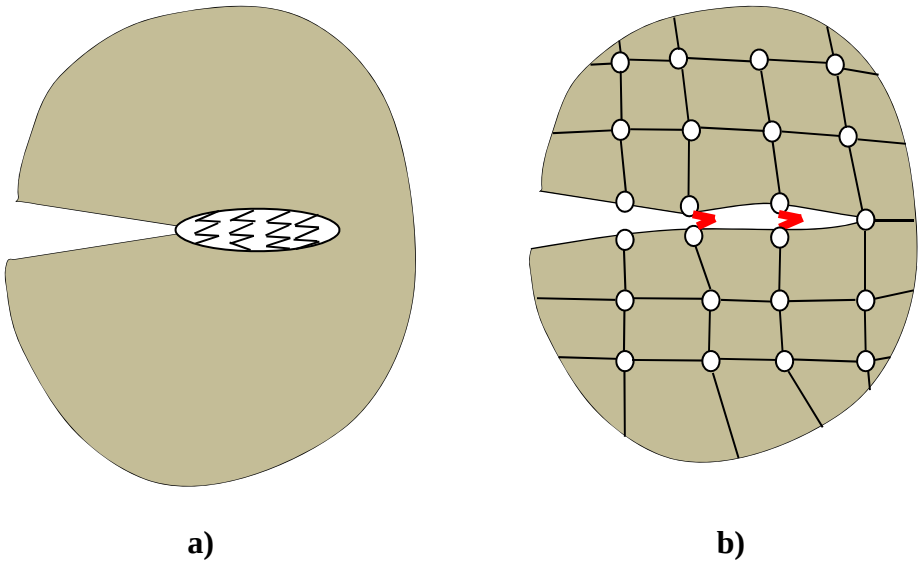

Figure 1: a) Schematic of a typical fracture process zone in quasi-brittle materials. b) In the Cohesive Zone method, the process zone is modeled using a traction-separation law between the nodes along the crack's free surfaces, and in the schematic shown, it is achieved using discrete cohesive elements (springs).

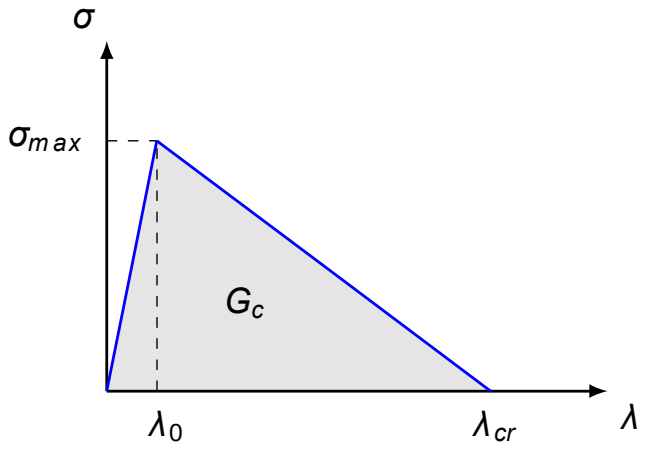

Figure 2: Typical bilinear traction-separation law used in cohesive zone models

The main benefit of the cohesive zone method is that in contrast to VCCT, it does not require the existence of an initial crack in the finite element mesh. Thus, this method can be used to simulate

the *initiation*, as well as the *propagation*, of the delamination crack in the composite material. As with the VCCT method, the regular implementation of the cohesive zone method requires the numerical representation of all of the interface layers that have the potential to undergo delamination, thus it requires knowing and modeling the delamination crack path explicitly prior to the analysis. Also, introducing cohesive zones in wide regions of the model will reduce the model's structural stiffness due to the flexibility of the cohesive zones. Attempts to increase the stiffness of the cohesive zones numerically will generally lead to excessive numerical noise and loss of solution stability.

It has been shown that in order to capture the correct crack propagation, the minimal element size should allow at least 2-3 cohesive elements to lie within the developed cohesive zone [4]. Since the actual cohesive zone in composite materials can be of a size that is 0.2-1 mm, this will result in an element size which ranges from around 0.07 to 0.5 mm. This element size is very small and is usually not practical for simulating large-scale structures utilized in industrial applications. In order to allow larger elements to be used, the maximum stress in the traction-separation law (σ_{max} in Figure 2) can be lowered, while keeping the critical strain energy release rate constant (by extending λ_{cr}). This will increase the numerical cohesive zone size, and will allow coarser elements to be used. On the other hand, it will contribute to further reduction of the structural stiffness due to the reduced stiffness of the cohesive elements. These issues limit the use of the cohesive zone method to relatively small-scale applications.

Local Insertion of Cohesive Zones

In this section, a novel simulation method is introduced that intends to effect a major improvement to the current available methods for simulating delamination in composite materials. It is implemented through the development of the Local Cohesive Zone algorithm (LCZ), which is a computer code that is closely linked to LS-DYNA. The algorithm is designed to simulate delamination damage growth in industrial size structures made of laminated composite materials. LCZ is an inherently *adaptive* algorithm, which means that it allows delamination damage to grow and evolve in the structure as the simulation progresses. This is achieved by locally *splitting* the structural elements through their thickness, and locally inserting cohesive zones to capture the delamination growth. The algorithm allows simulating both static and dynamic loading conditions, and is well suited for parallel execution across high performance computing clusters.

Figure 3 demonstrates the execution flow of the developed LCZ algorithm which controls LS-DYNA's execution externally. It receives the LS-DYNA input file as an input from the user, as well as the material models, boundary conditions, and other execution related parameters. The algorithm executes independently and controls the LS-DYNA run until the final termination time is reached.

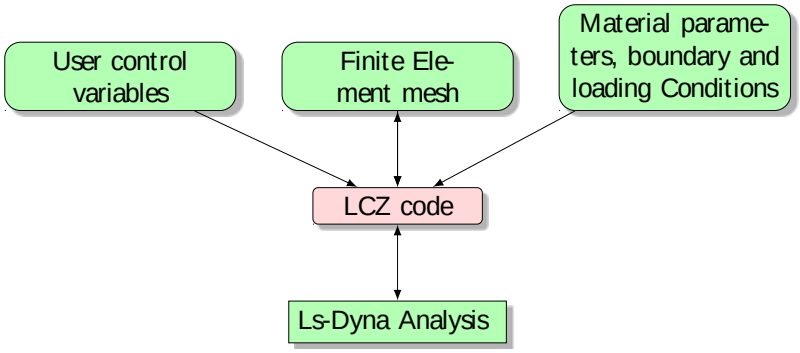

Figure 3: General execution flow diagram for the LCZ algorithm

The algorithm is based on the following principles:

- The structure made of the composite material can be modeled using only one layer of structural elements.
- Delamination cracks and crack-growth paths *do not* need to be defined in the model prior to the analysis, as they are created adaptively as the simulation progresses.
- Once an *element splitting criterion* is met in one or more of the structural elements, the elements are locally split *through their thickness*, and cohesive zones are introduced between the newly created surfaces.
- The cohesive zones are locally and *adaptively* introduced in the model, *only* at specific locations where delamination is about to take place, thus, the computational cost is kept to a minimum. A user-defined geometrical radius *R* is used to determine the size of the geometrical region where the cohesive elements will be introduced. It is important to note that this element-splitting process does not resemble the physical delamination in the material. It is merely a means of locally planting the cohesive zones in the structure. These cohesive zones serve as the potential regions for delamination growth. The actual delamination propagation and growth is controlled and simulated by these zones, which are introduced to the model by the element splitting process.
- The dominant process zone is correctly captured by the cohesive traction-separation law. Altering the cohesive law, allows coarser meshes to be used in the model, with a minimal effect on the structural stiffness, as the cohesive zones are embedded in relatively small geometrical regions in the model.
- The algorithm allows the local cohesive zones to propagate adaptively and migrate in the model as the delamination damage grows and evolves in the structure. This unique feature is graphically presented in the following benchmark problem (Figure 8).

Verification

In order to verify the performance of the basic algorithm, a simple Double Cantilever Beam (DCB) example, described in detail in [5] was simulated using the LCZ algorithm (Figure 4). The example consists of a beam of length, $L = 100mm$, thickness, $h = 3mm$ and width of $20mm$. The beam consists of a pre-existing crack of an initial length, $a = 30mm$. A splitting normal displacement Δ in the global z -direction, is applied at the tip of the beam.

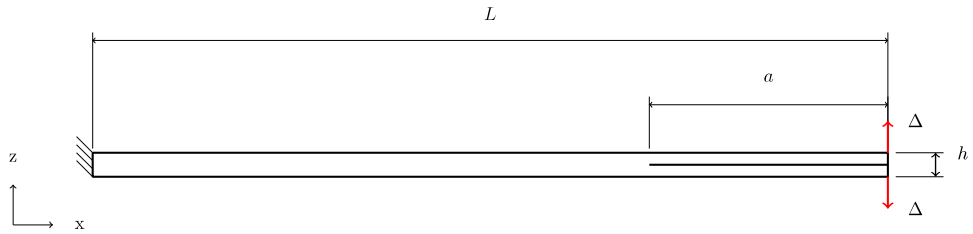

Figure 4 - DCB numerical test case

The model was simulated using the following two configurations:

- **Case 1, Conventional Cohesive Zone Method (Figure 5):** The beam was modeled using two layers of thick-shell elements (*ELEMENT_TSHELL, ELFORM=5), with the expected crack growth path pre-defined prior to the analysis. The crack path was defined using a layer of solid cohesive elements, located along the interface layer of length L minus a along the beam. The initial crack, of length a, was defined in the model by using two layers of thick-shell elements with no cohesive elements in between. The LCZ algorithm *was* not used in this analysis. Thus, this case is identical to the classical cohesive zone method, where the crack path is defined prior to the analysis.

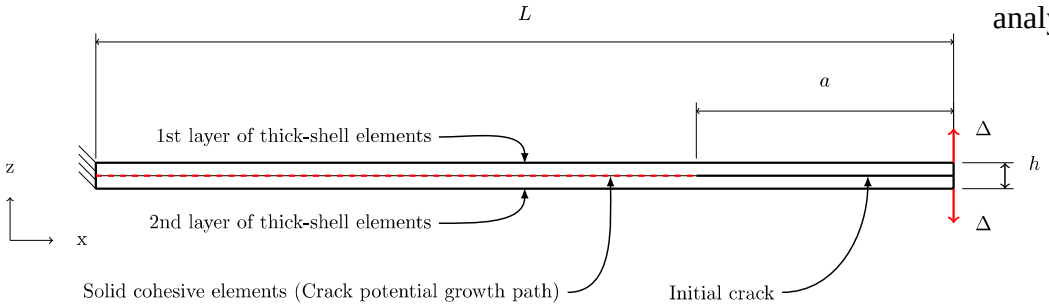

Figure 5 - DCB test case 1. The beam consists of *two* layers of thick shell elements, with cohesive elements pre-defined along the potential delamination crack path.

- **Case 2 , Local Cohesive Zone Method (Figure 6):** The model was built using only *one layer* of thick-shell elements through its thickness, along the un-cracked section of the beam. Only the initial crack of length a was defined in the model. The cracked region was modeled using two layers of regular shell elements (*ELEMENT_SHELL, ELFORM=16), each describing one surface of the cracked section. *No cohesive elements are present in the model prior to the analysis, and the crack-growth path is not defined*. The LCZ algorithm was implemented to predict the delamination crack growth, and embed the local cohesive zones where and when needed.

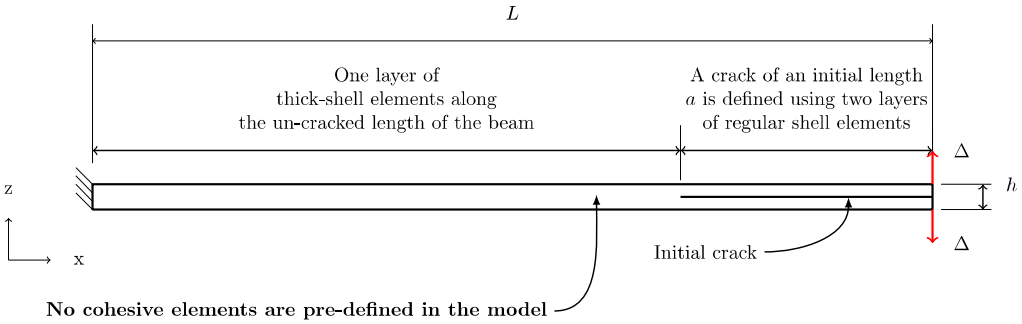

Figure 6 - DCB test case 2. The beam is made using *one* layer of thick shell elements, along the un-cracked section of the beam. No cohesive elements are pre-defined in the model. The LCZ algorithm was implemented to predict the crack growth.

To further simpl ify the problem, an elastic-isotropic material model was chosen for the continuum elements. The following material parameters were used:

Elastic modulus, $E = 135.3\ [GPa]$, and Poisson's ratio, $\nu = 0$

The traction-separation law, used for the cohesive elements, had the following properties:

$$G_c = 0.28\ \left[\frac{N}{mm}\right],\ \ \lambda_0 = 10^{-7}[mm],\ \ \sigma_{max} = 57\ [MPa]$$

For both cases 1 and 2, the in-plane dimensions of the structural elements were $2mm \times 2mm$.

The force vs. displacement results from the analysis of cases 1 and 2, together with the prediction of the analytical model [5] is shown in Figure 7. It can be seen that both the LCZ algorithm and the conventional cohesive zone method results (cases 1 and 2), are in good agreement with the analytical model.

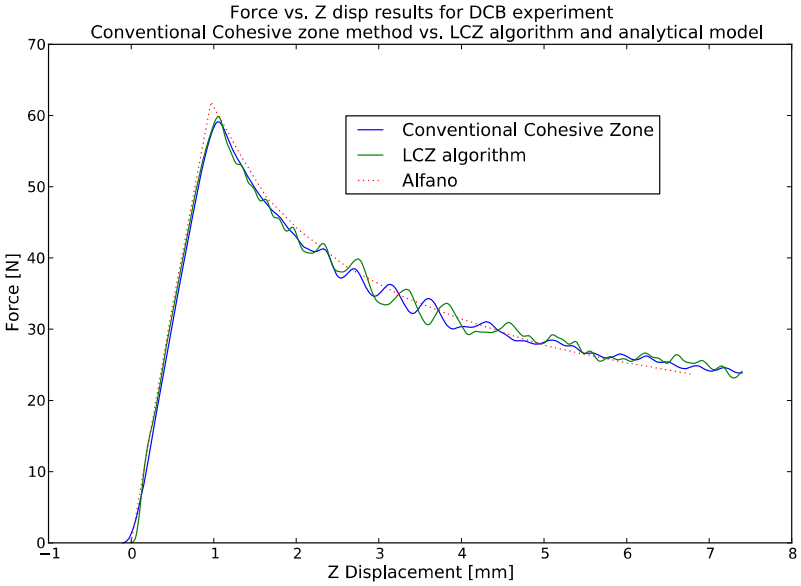

Figure 7- Force vs. displacement result for the simple DCB model. The LCZ algorithm prediction (case 2) is shown superposed on the conventional Cohesive Zone method (case 1) and the analytical model prediction [5].

Typical results from the DCB splitting simulation are shown in Figure 8. Here, the cohesive zones are identified with a brown color. The figure demonstrates the local cohesive zones migration and propagation into the structure as the crack opens. The LCZ algorithm ensures that the cohesive zones will only be created where needed, while keeping the computational cost to a minimum.

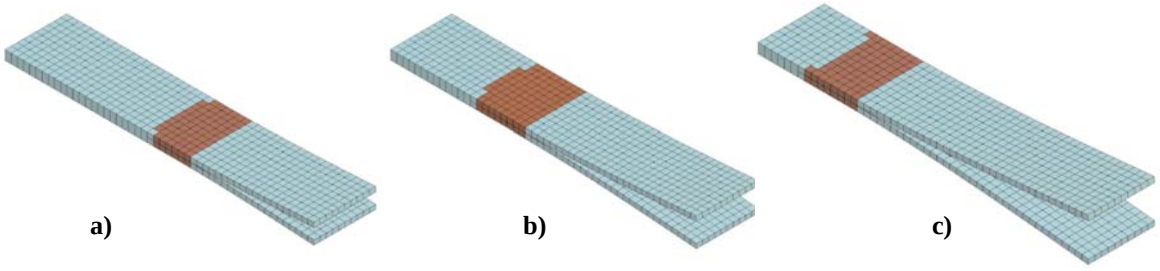

Figure 8 – Isometric view of the DCB benchmark example. The migrating cohesive band is shown as the dark region. Through–thickness element splitting can also be seen as the delamination crack propagates from state a) to c).

These initial results are encouraging, and prove that for the simple Mode I delamination loading case considered here, local and adaptive insertion of cohesive zones into a model can correctly capture the delamination crack propagation.

Conclusions

The work presented in this paper, includes the development of a robust numerical framework for the simulation of delamination in composite and laminated materials, with the following benefits:

- The method allows modeling the structure without *a priori* knowledge or definition of the delamination cracks' location in the analysis, i.e. cracks initiate and evolve as the simulation progresses.
- The method has only a minor effect on the overall structural stiffness before the onset of delamination, as the cohesive zone is locally embedded in the structure only where and when needed.
- The method can correctly capture the mechanical behavior of the fracture process zone to a level that is required for the simulation of the delamination damage propagation.
- The method allows using relatively coarse meshes to further reduce the computational cost.
- The method can be combined with other in-plane damage theories (e.g. [6]) to capture complex failure mechanisms in the material. The interaction of delamination damage with other damage mechanisms in composite materials is the subject of ongoing research, and is resulting in further development of the algorithm.
- The method has the potential to allow simulation of delamination in large-scale composite structures employed in industrial applications.

Initial results from the developed algorithm are encouraging and prove that the local and adaptive insertion of cohesive zones into a model can effectively capture the delamination crack propagation in the structure.

References

[1] A. S. Kaddour, M. J. Hinton, P. A. Smith and S. Li, "A comparison between the predictive capability of matrix cracking, damage and failure criteria for fibre reinforced composite

laminates: Part A of the third world-wide failure exercise," *J. Composite Mater.*, vol. 47, pp. 2749-2779, 2013.
[2] G. A. O. Davies and X. Zhang, "Impact damage prediction in carbon composite structures," *Int. J. Impact Eng.*, vol. 16, pp. 149-170, 1995.
[3] E. F. Rybicki and M. F. Kanninen, "Finite element calculation of stress intensity factors by a modified crack closure integral," *Eng. Fract. Mech.*, vol. 9, pp. 931-938, 1977.
[4] P. W. Harper, L. Sun and S. R. Hallett, "A study on the influence of cohesive zone interface element strength parameters on mixed mode behaviour," *Composites Part A: Applied Science and Manufacturing*, vol. 43, pp. 722-734, 2012.
[5] G. Alfano and M. A. Crisfield, "Finite element interface models for the delamination analysis of laminated composites: Mechanical and computational issues," *Int J Numer Methods Eng*, vol. 50, pp. 1701-1736, 2001.
[6] A. Forghani, N. Zobeiry, A. Poursartip and R. Vaziri, "A structural modelling framework for prediction of damage development and failure of composite laminates," *J. Composite Mater.*, vol. 47 (20-21), pp. 2553–2573, 2013.