A VCCT-Cohesive Approach for the Efficient Modelling of Delamination in Composite Materials

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Abstract

The accurate modelling of delaminations is necessary to capture the correct behavior of composite structures subjected to demanding loads. While the use of cohesive elements is valid when the discretization is smaller than the failure process zone [1], for many composite materials it implies using a fine mesh, typically smaller than 1.0 mm, leading to excessive computational cost for large structures. On the contrary, the Virtual Crack Closure Technique (VCCT) allows the prediction of delamination growth in larger elements [2] but lacks of an energy dissipation mechanism. Therefore, it leads to excessive vibrations when the delamination propagates in dynamic analyses. The present work aims to combine the best of both methods in order to develop a viable solution for large structures, allowing for coarser meshes than what is possible to use today. To do so, the VCCT is used as a failure criterion to predict damage initiation while a cohesive-like model is added to dissipate the released energy. The model has been implemented in LS-DYNA in the frame of an adaptive user element recently published [3,4]. The model has been validated with Double Cantilever Beam, End-Notched Flexure and Mixed-Mode Bending tests. It demonstrates the ability of the method to accurately model delamination with larger elements and higher stable time step.

1 Introduction

Delamination is considered as a critical failure risk of layered Fiber-Reinforced Polymers (FRPs) in the transportation industries. Although it represents a challenge, conservative design allowables can be developed to avoid the appearance of such out-of-plane cracks in static load cases. However, when aiming to capture the correct behavior of FRPs in crash loads, it is fundamental to be able to model the delamination growth and the energy dissipation mechanisms associated with it. Indeed, delamination drastically influence the overall response of the structure since it considerably lowers the stiffness of the laminate.

The introduction of cohesive models has met this modelling need. However, due to the brittle nature of the layer interfaces, the associated Failure Process Zone (FPZ) is usually small, typically smaller than 1 mm. As a consequence, the mesh discretization has to be smaller than the FPZ [1], leading to highly refined meshes. Additionally, the cohesive model uses an artificial interface stiffness in order to detect damage initiation. This artificial stiffness, which must be high in order to avoid adding unrealistic compliance to the model, however reduces the stable time step of the numerical model. The increased computational cost resulting from these restrictions makes the cohesive models unusable for large structures.

Another method to model delamination propagation is the Virtual Crack Closure Technique (VCCT). To predict the growth of the crack, the VCCT compares the elastic energy that would be released by increasing the crack length to the fracture toughness of the interface. This method has the main advantages that it has been proven to be accurate for larger elements [2] and that it does not introduce interface stiffness; making it computationally efficient. However, since the VCCT does not have any energy dissipation mechanism associated, uncontrollable vibrations occur in explicit simulations when suddenly releasing the interface along an element's length.

The present method, inspired by a work from Mabson et al. [5], is based on the VCCT in order to predict delamination growth. Using the forces at the crack tip and the opening (or displacement jump) behind it, the Energy Release Rate (ERR) is computed. The interface between two elements is then released when the ERR surpasses the fracture toughness. In order to dissipate the energy associated with the crack growth, it is herein proposed to add a decreasing force at the released node pairs. This effectively creates a cohesive law, with non-zero initial force, which relates the force to the opening at the node interface. This cohesive law is further adapted to dissipate the correct energy associated with the fracture mode detected by the VCCT.

The final purpose of this work is to be used in the frame of an adaptive modelling strategy where the model is refined only where necessary throughout the simulation. This adaptive user element has recently been published [3,4]. Therefore, the implementation of the VCCT-cohesive approach has been made into the same subroutine.

Standard delamination growth tests have been used in order to validate the method. For this purpose, Double Cantilever Beam (DCB), End-Notched Flexure (ENF) and Mixed-Mode Bending (MMB) tests have been simulated and the results compared to analytical solutions based the corrected beam theory.

2 Theory

In this section, the theory of the modelling strategy is divided into three subsections. The first subsection exposes the refinement state in which the problem is based, the second subsection details the VCCT method used while the third subsection introduces the cohesive law.

2.1 Procedure

In the frame of the previously mentioned adaptive user element, the simulation starts in an unrefined state with a single through-the-thickness thick shell element defined by 8 base nodes (corresponding to **`*SECTION_TSHELL`** with **`ELFORM 5`**). During the simulation, where necessary the model can be through-the-thickness refined with weak (strain) or strong (displacement) discontinuities. This is achieved by respectively adding 4 or 8 new nodes at the desired ply interface. The laminate is suitably split between the newly defined top and bottom elements. In the case of a strong refinement, a cohesive element is introduced in order to model delamination propagation. For more detail on the adaptive procedure, refer to [3].

The present work is focused on finding a substitution to the cohesive elements. As explained previously, the use of cohesive elements indirectly results in a high computational cost due to the fine mesh and low time step they entail. To achieve this, only the final state of the adaptive procedure, where the model is already refined with a strong discontinuity, is used in the present work. Additionally, only mode I and mode II are considered. In order to model a bonded interface, the nodes at the strong refinements are coincident in space and tied together by imposing equal acceleration on both nodes [3]. If a cracked interface is to be modelled, the refined nodes are set free from each other and a frictionless penalty contact is introduced. An illustration of the initial state of refinement for the present study is presented in Fig. 1.

In order to model delamination growth, the VCCT is computed at the tied nodes. If the criterion is met, the tied is released and a cohesive law with non-zero initial force is introduced.

2.2 VCCT

The VCCT uses the hypothesis of self-similar growth of the crack to measure the force and the opening at two different node pairs. The ERR corresponding to the different modes are evaluated by means of the following expressions:

$$G_{\mathrm{I}} = \frac{1}{2A^i} F_{\mathrm{I}}^i \langle \Delta_{\mathrm{I}}^{i-1} \rangle \quad (1)$$

$$G_{\mathrm{II}} = \frac{1}{2A^i} F_{\mathrm{II}}^i \Delta_{\mathrm{II}}^{i-1} \quad (2)$$

where G_α is the ERR corresponding to the mode α ($\alpha = \mathrm{I}, \mathrm{II}$), F_α^i and Δ_α^i are respectively the tied force and the opening in mode α at the node pair i and A^i is the area which will be opened by releasing the tied condition at node pair i, see Fig. 1.

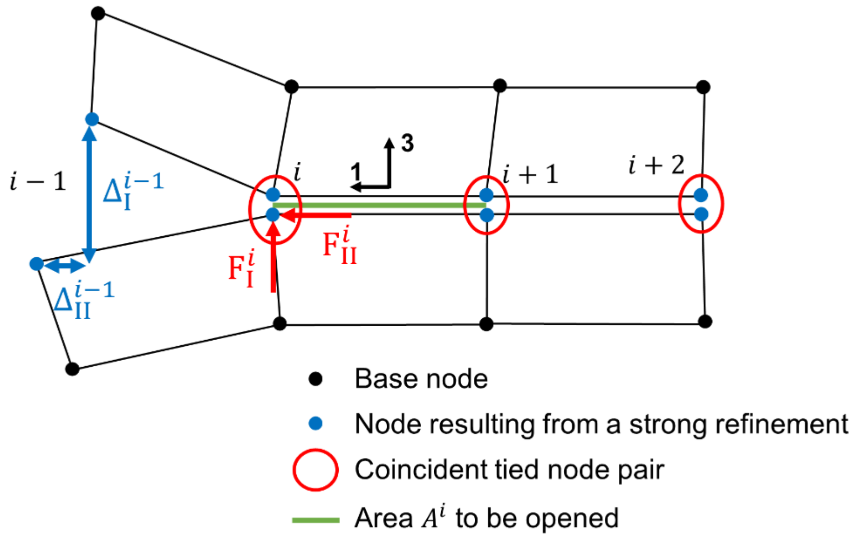

Fig.1: Crack tip configuration with a strong refinement.

The total ERR G_T is the sum of the 2 modes:

$$G_\mathrm{T} = G_\mathrm{I} + G_\mathrm{II}. \tag{3}$$

The damage initiation criterion is met when the total energy G_T surpasses the critical energy G_c corresponding to the current mixed-mode ratio B. The mode ratio B is defined as

$$B = \frac{G_\mathrm{II}}{G_\mathrm{T}} \tag{4}$$

and G_c is calculated using the Benzeggagh-Kenane (BK) equation [6]:

$$G_\mathrm{c} = G_\mathrm{Ic} + [G_\mathrm{IIc} - G_\mathrm{Ic}]B^\eta \tag{5}$$

where G_Ic and G_IIc are the pure mode fracture toughnesses of the interface and the exponent η is a parameter to be determined experimentally.

2.3 Cohesive

Once the VCCT criterion is met, the tied condition at the node pair will be released. If no energy dissipation mechanism is used, the strain energy corresponding to a crack growth of one element's length would suddenly be released leading to uncontrollable vibrations, see Fig. 5. To be specific, the vibrations would rapidly trigger the VCCT criterion of the next pair of nodes, $i+1$. The vibrations would continue until the entire sample has delaminated under a very short time.

To avoid such vibrations, a smooth transition has to be ensured from the tied forces at node i where the VCCT criterion has been met, F_I^i and F_II^i, to a totally free interface while dissipating the correct energy A^iG_c. In the following, the cohesive law is presented for any given node pair and the tied forces that triggered the VCCT are noted F_α^0. The cohesive law is expressed by the following expression:

$$F_\alpha = F_\alpha^0(1-D), \tag{6}$$

with the total damage:

$$D = (1-B)d_\mathrm{I} + Bd_\mathrm{II}. \tag{7}$$

The mixed-mode B has been determined by the VCCT and

$$d_{\mathrm{I}} = \max_{0 \le s \le t} \left\{ \frac{\langle \Delta_{\mathrm{I}} \rangle}{\Delta_{\mathrm{I}}^{\mathrm{f}}} \right\} \tag{8}$$

$$d_{\mathrm{II}} = \max_{0 \le s \le t} \left\{ \left| \frac{\Delta_{II}}{\Delta_{\mathrm{II}}^{\mathrm{f}}} \right| \right\} \tag{9}$$

where t is the current time and $\Delta_{\alpha}^{\mathrm{f}}$ is the opening at which the energy G_{α} would be consumed by linear softening:

$$\Delta_{\alpha}^{\mathrm{f}} = \frac{2G_{\alpha}A}{F_{\alpha}^{i}}. \tag{10}$$

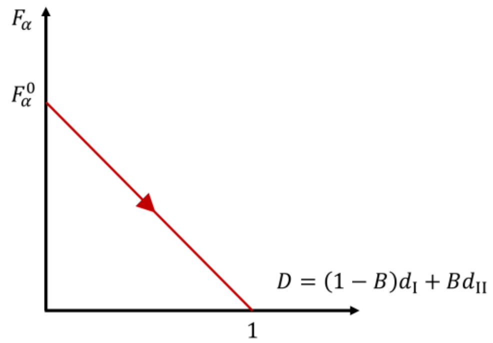

Fig.2: Cohesive load-opening linear law.

The linear softening is presented in Fig. 2. Equation (6) and (7) state that both modes are equally softened and that each mode contributes proportionally to its importance in the ERR into the total damage D. For instance, in the case of a pure mode I loading such as a DCB test, $B = 0$ leads to D being entirely defined by the mode I opening: $D = d_{\mathrm{I}}$. It is worth noting that $\Delta_{\mathrm{I}}^{\mathrm{f}}$ and $\Delta_{\mathrm{II}}^{\mathrm{f}}$ of node pair i are equal to the openings at node pair $i - 1$ with which the VCCT has been triggered.

3 Results

DCB, ENF and MMB tests have been simulated in order to validate the model. The specimens are 100 mm long and 4 mm thick. The longitudinal and transverse element lengths are respectively 5 mm and 2 mm. For comparison, if cohesive elements were to be used, the maximum in-plane element length would be of the order of 1 mm [1]. Two elements in the width direction are used, forming a total specimen width of 4 mm. The original element thickness is 4 mm but a strong refinement is initiated at the middle plane. Therefore, one through-the-thickness element is used per arm, as shown in Fig. 1. The pre-crack length is 25 mm for DCB and MMB and 35 mm for ENF. The bonded and pre-cracked areas are numerically defined by respectively adding and setting free the tied condition at the refined interface, see Fig. 1. For the MMB tests, the mixed-mode ratio has been fixed to 50% by setting the lever distance to 41.08 mm. The dimensions of the specimens and the load configurations are presented in Fig. 3.

The laminate is fully unidirectional with fibers orientated along the longitudinal direction of the specimens. A prototype material has been used; its properties are summarized in Table 1. The results are compared to analytical solutions based on the corrected beam theory [7,8,9]. It is worth mentioning that all the simulations have been run without damping. The stable time step used is 2.6×10^{-7} s.

E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	ρ (kg.m^{-3})
120	10	5	3.5	1500

$\nu_{12} = \nu_{13}$	ν_{23}	G_{Ic} (kJ.m^{-2})	G_{IIc} (kJ.m^{-2})	η
0.3	0.4	0.2	0.8	2.0

Table 1: Material properties used in the simulations.

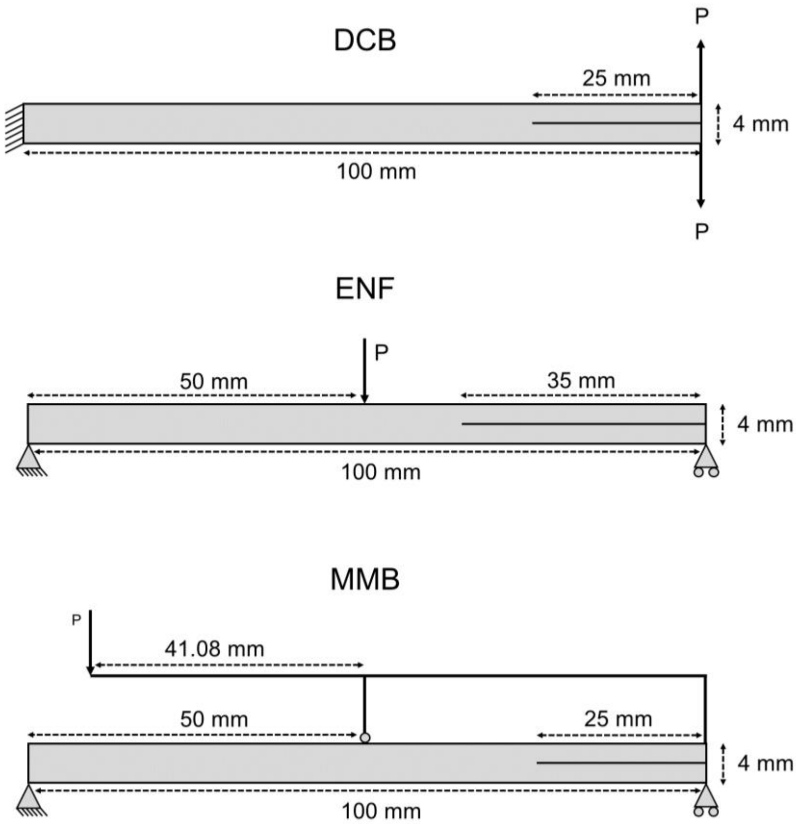

Fig.3: Test specimen dimensions and load configurations.

3.1 DCB

The load-displacement results for the DCB test can be seen in Fig. 4. The results of the present method are in agreement with the analytical solution. Relatively low vibration can be observed.

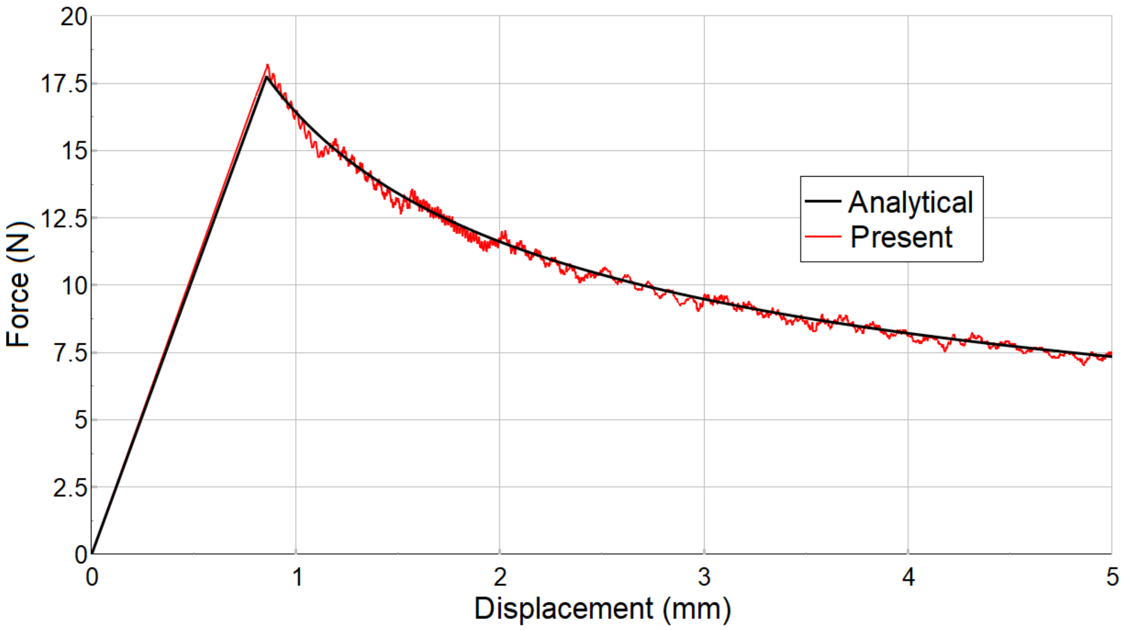

Fig.4: Results for the DCB test for mode I crack propagation.

To demonstrate the importance of the energy dissipation mechanism for the correct propagation of the crack, the results obtained without cohesive law are shown in Fig. 5. To be specific, when the VCCT criterion is met at a node pair, the tie is simply deactivated. If no damping is used (gray curve), uncontrollable vibrations occur at the moment the first node pair is released. The vibrations continue for the rest of the simulation. In order to control those vibrations, a very high damping is needed. The blue curve is obtained by setting **`VALDMP`** = 10,000 s^{-1} in the keyword **`*DAMPING_GLOBAL`**. Although the damping coefficient is high, each time a node pair is released the vibrations make the crack front propagate through several elements.

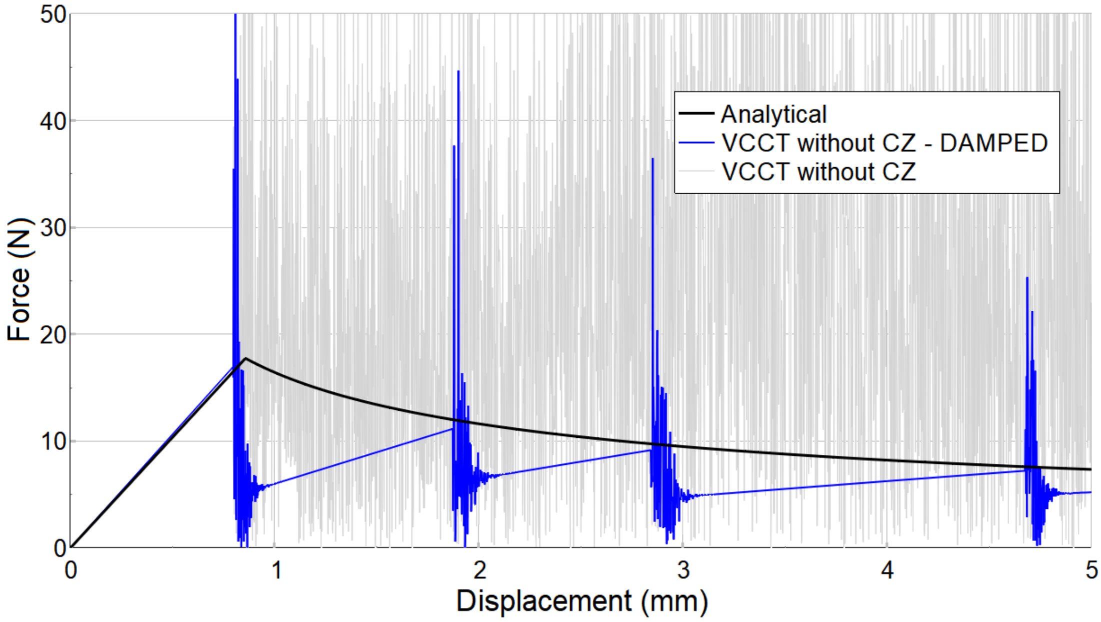

Fig.5: Results for the DCB test without cohesive law.

3.2 ENF

The load-displacement results for the ENF test can be seen in Fig. 6. The results of the present method are in agreement with the analytical solution. Relatively low vibration can be observed.

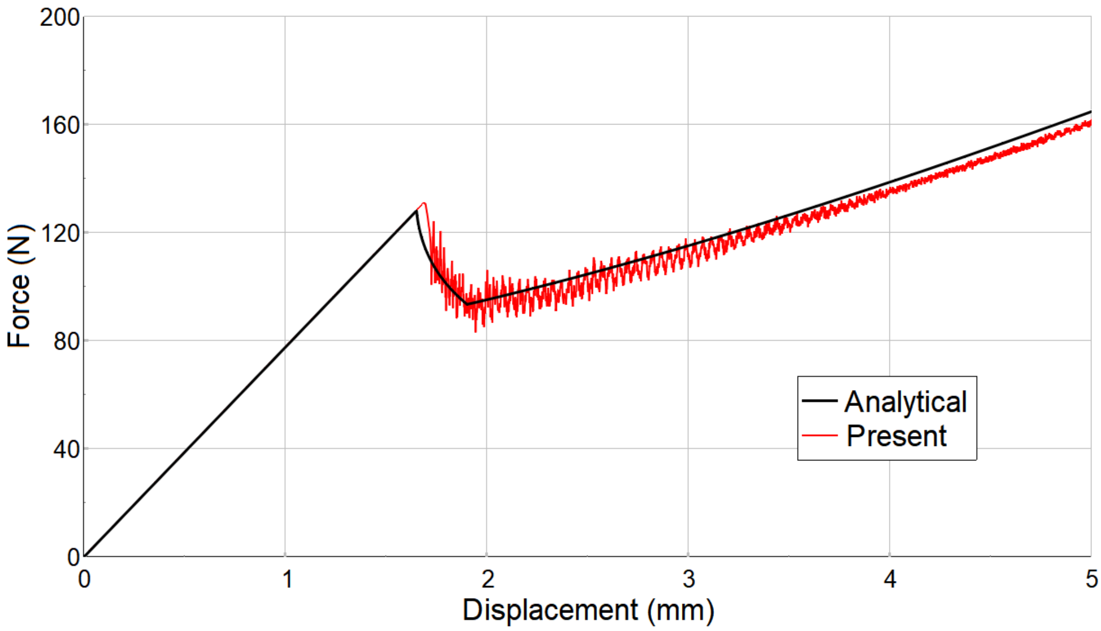

Fig.6: Results for the ENF test for mode II crack propagation.

3.3 MMB

The load-displacement results for the MMB test can be seen in Fig. 7. The results of the present method are in agreement with the analytical solution. Relatively low vibration can be observed. A vertical drop in force can be observed at a displacement of about 1.8 mm which is caused by a sudden crack propagation. For this reason, the simulation time of this test has been made longer in order to avoid instabilities.

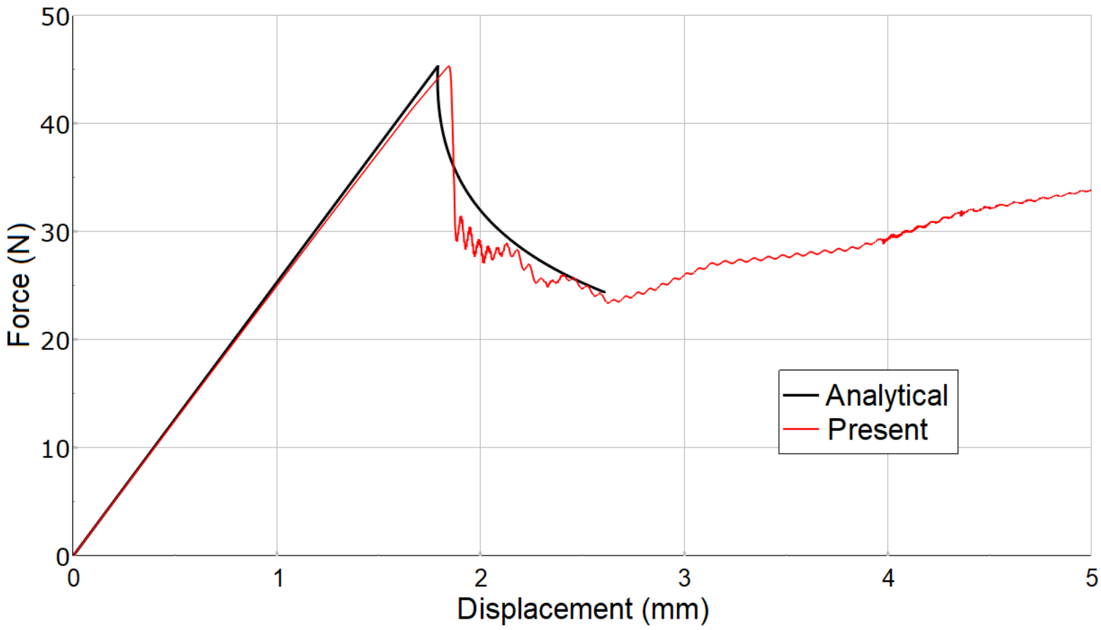

Fig.7: Results for the MMB test for mixed-mode crack propagation, $B = 0.5$.

4 Discussion

The present work serves as a proof of concept for the development of a method capable of modelling delamination in large structures. However, several challenges will have to be overcome in order to fully reach this purpose.

Firstly, the present cohesive model does not have unloading capability. In other words, if the opening decreases the forces are kept constant. Thus, upon a decreasing opening d_{I} and d_{II} keep their values from the maximum openings reached and so does D. Therefore, in the case of a large structure with a complex load, it is likely that an area of the model would retain a constant (but unrealistic) interface force throughout the rest of the simulation.

Another challenge is the ability of the VCCT to predict damage initiation in irregular meshes and cases where the delamination front is not aligned with the mesh. Indeed, the VCCT uses the hypothesis of self-similar growth which is valid only when the mesh is regular.

These challenges will be treated in future publications by the authors.

5 Conclusions

A method for the propagation of delamination crack in large elements has been presented. It uses the VCCT as a damage initiation criterion and a cohesive law in order to absorb the correct energy resulting from the newly opened area.

The method is numerically efficient as it allows the use of much larger element (e.g. 5 mm) than the conventional cohesive zone modelling (usually smaller than 1 mm). Additionally, no artificial stiffness is introduced meaning that the stable time step is not limited by the interface.

The method has been used for DCB, ENF and MMB tests with 5 mm-long elements. The good results demonstrate the ability of the method in modelling delamination propagation with large elements. The proposed modelling strategy opens possibilities for the development of an efficient method capable of modelling delamination in large structures.

6 Acknowledgements

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7 Literature

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