23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

MODELLING DELAMINATION OF COMPOSITES USING COHESIVE ZONE TECHNIQUES

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Composite materials are used in many specialised armour applications such as spall-liners and inserts in bullet proof vests. Fibre reinforced composites with a laminate lay-up (or laminates) are the most typically used composites. When laminates are subject to projectile impact, very local failure of the different laminate components is observed, such as fibre fracture, matrix failure and delamination. When failure occurs, the laminate is locally weakened. From a practical point of view, it is desirable to be able to predict how especially delamination weakens the structure during and after the impact process.

In this research, the focus is on predicting mode I delamination and more specifically the amount and the exact location of delamination in the laminate. Predicting delamination of a laminate due to projectile impact is one of the most challenging subjects in (fracture) mechanics. This is because the behaviour of the laminate highly depends on the mixed mode behaviour under very high strain rates. In addition, it is in general difficult to obtain realistic material properties at such high strain rates.

In this research, delamination is modelled using cohesive zones between layers with a traction separation criterion. Using cohesive zone techniques, it is possible to describe mode I fracture initiation and fracture development up to failure. This technique is very general and can be used to predict delamination of other laminates with only minor adjustments.

Laminates combine the best properties of different materials and thus give the possibility to design light weight structures. If armour panels in ground vehicles can be made light weight, the mobility of the vehicles increases. Laminates that are used in armour applications are subject to projectile impact. When a projectile impacts on a laminate, different fracture phenomena occur in the different components of the laminate. One of the fracture phenomena that is still not well understood is delamination under high strain rates. Because delamination locally weakens a laminate, it is desirable to be able to predict delamination initiation and development in a laminate and its effect on the structure.

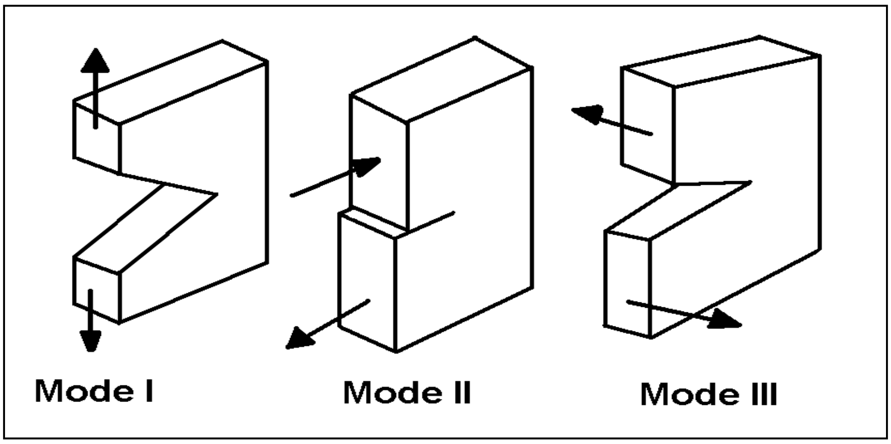

Figure 1 Delamination modes

There are three modes of delamination, see figure 1. Mode I is the so-called opening mode and mode II and mode III represent the in-plane and out-of-plane shear modes respectively, see [1]. Usually, mode II and mode III delamination are not considered, because the effects of mode II and mode III delamination are almost negligible in an impact situation in comparison with mode I delamination.

In the past, projectile impact on laminates has mainly been modelled using continuum models, for example in [2] and [3]. This means that the initiation and development of delamination cannot be accurately described, because the modelling scale is on a macro level. Other models assume that delamination can be described by representing the laminate as a set of layers in which layers with fibre properties and layers with matrix properties alternate. The matrix is then modelled as an isotropic layer and the fibres are represented by layers with orthotropic constitutive behaviour. This is not physically correct, because the decoupling is not done correctly. Another approach to implement mode I delamination that is used in the past is the Virtual Crack Closure Technique (VCCT) [4]. VCCT is a technique that is similar to the cohesive zone technique. The main difference is that when modelling is done using VCCT, the location of the fracture surface must be known in advance. This is not the case for cohesive elements with which the whole fracture process from initiation through development and eventual cracking can be described. Because of the aforementioned reasons, cohesive zones will be used to uncouple the adhesive behaviour and the fibre material properties in this research.

LAMINATE MODEL

As stated above, a numerical model is made in order to simulate projectile impact on a UHMW-PE laminate. UHMW-PE laminates are in general non-woven cross plies. In figure 2, two orthogonal layers consisting of filaments and a small amount of matrix material are depicted on the left. The layers in this picture each have a thickness of 0.05 *mm*. A UHMW-PE panel of 5 *mm* thickness typically contains tens of layers of filaments. The exact number of layers depends on the application of the laminate it is designed for and thus on production parameters.

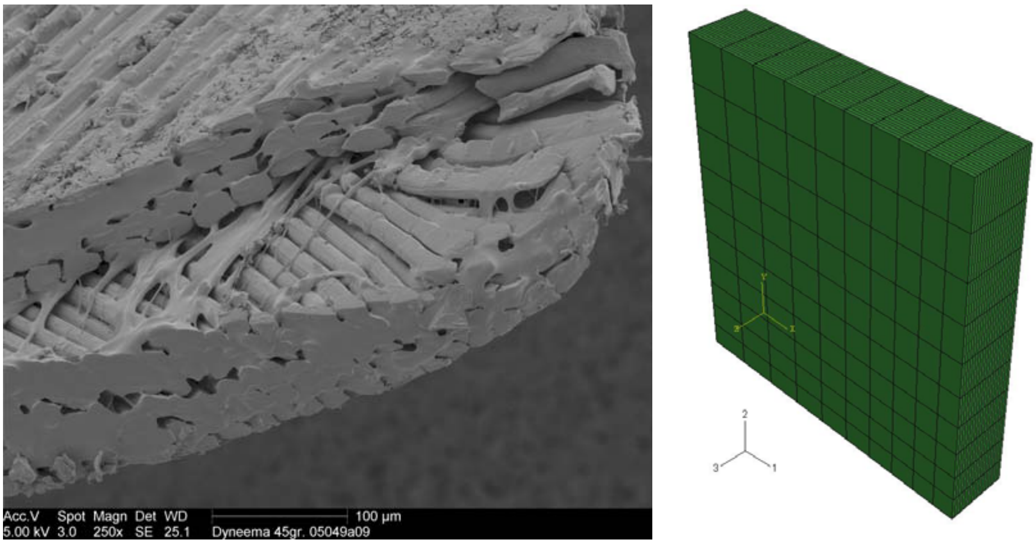

Figure 2 two filament layers (left), laminate model (right)

The computations are done in ABAQUS/Explicit. The computational model is built up from several layers with fibre properties with cohesive zones with zero thickness in between the filament layers, see figure 2. This is done to uncouple the material properties of the filaments from the adhesive properties between the layers. Because of computational considerations, the laminate model does not consider each single filament. Currently, twenty physical layers of filaments are represented by one layer in the model. The filament layers in the model have the properties of the filaments only. This is done in order to uncouple the adhesive properties between the layers in a correct way. Because of symmetry, the filament layers are given orthotropic elastic properties. The constitutive behaviour is given by:

$$\bar{\sigma} = \overline{\overline{D}} \cdot \bar{\varepsilon} = \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix} = \begin{bmatrix} D_{1111} & D_{1122} & D_{1133} & 0 & 0 & 0 \\ D_{1122} & D_{2222} & D_{2233} & 0 & 0 & 0 \\ D_{1133} & D_{2233} & D_{3333} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{1212} & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{1313} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{2323} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{bmatrix} \tag{1}$$

In the length direction of the filaments, the tensile modulus of the filaments is taken as the value for the stiffness in that direction. From ultrasound tests, it turns out that the modulus in thickness direction is about ten times lower than the in-plane moduli of the UHMW-PE laminate and this is also the value that is used in this model. Because the resistance to shear loading is not much influenced by the small amount of matrix material that is contained in a layer, all shear moduli are small compared to the in-plane tensile moduli. However, there is no method to exactly determine the values for the shear moduli and at the moment these values are educated guesses. In order to guarantee stability of the solution, the Drücker criteria are used (with D the stiffness matrix):

$$\begin{gathered} \det \overline{\overline{D}} > 0 \\ D_{1111}, D_{2222}, D_{3333}, D_{1212}, D_{1313}, D_{2323} > 0 \\ \left| D_{iijj} \right| < \sqrt{D_{iiii} \cdot D_{jjjj}} \end{gathered} \tag{2}$$

From post-impact analysis, it is found that filaments behave almost entirely elastic up till failure, see figure 3. In this figure, it is seen that almost no yielding occurs due to impact. Because failure can only be implemented when plasticity is specified, a plastic behaviour is implemented. The amount of plasticity before failure is small in order to make it realistic. An energy criterion is used to implement failure of the filaments.

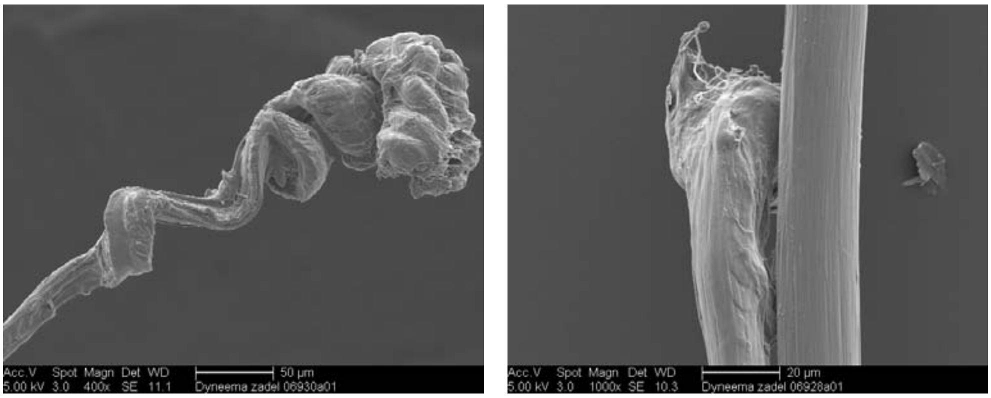

Figure 3 fractured filament due to filament at a magnification of 400 (left) and 1000 (right)

Using cohesive zone techniques to model the adhesive properties gives a more physically correct description of the delamination problem, compared to using continuum elements. Cohesive zones can be depicted as a spring-damper system. The cohesive elements use a traction separation law constitutive behaviour in this model:

$$\begin{bmatrix} t_n \\ t_s \\ t_t \end{bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{bmatrix} \tag{3}$$

Because the parameters K_{ii} are not determined very accurately, the values are more or less educated guesses. The values K_{ii} also have to fulfil stability criteria that are similar to the Drücker criteria:

$$\begin{aligned} &\det \overline{\overline{K}} > 0 \\ &K_{nn}, K_{ss}, K_{tt} > 0 \\ &\left| K_{ij} \right| < \sqrt{K_{ii} \cdot K_{jj}} \end{aligned} \tag{4}$$

The adhesive properties between the filament layers are modelled using cohesive zones. Using cohesive zones, it is possible to model the initial loading, the initiation of damage between the filament layers and the propagation of damage that leads to the final failure at the bonded interface. One of the greatest benefits of this method is that a zone where possibly delamination can occur need not to be cracked at the beginning of the simulation. The exact locations (among all areas modelled with cohesive elements) where cracks initiate, as well as the evolution characteristics of such cracks, are determined as part of the solution using the energy release rate.

The ball shaped projectile is modelled as a rigid body shell. A ball shape is used to avoid with sharp-edge discontinuities. Some simulations with the same projectile geometry using continuum elements are made; however the results were almost the same as the results when using a rigid body shell. Therefore, rigid body shells are used in the remainder of this research.

FRACTURE DEVELOPMENT

The results of the simulations are qualitatively compared with experimental results. In order to get track of the delamination that develops in the impacted laminate in time, high speed video techniques are used to record the impact event. From these experiments, it is seen that mode I delamination is initiated some time after impact due to the interaction between the longitudinal and transversal waves. The fracture between the layers first occurs close to the impact point and the fracture surface develops away from the impact point. After that, new fracture surfaces develop further away from the impact point and again these fracture surfaces develop away from the impact point.

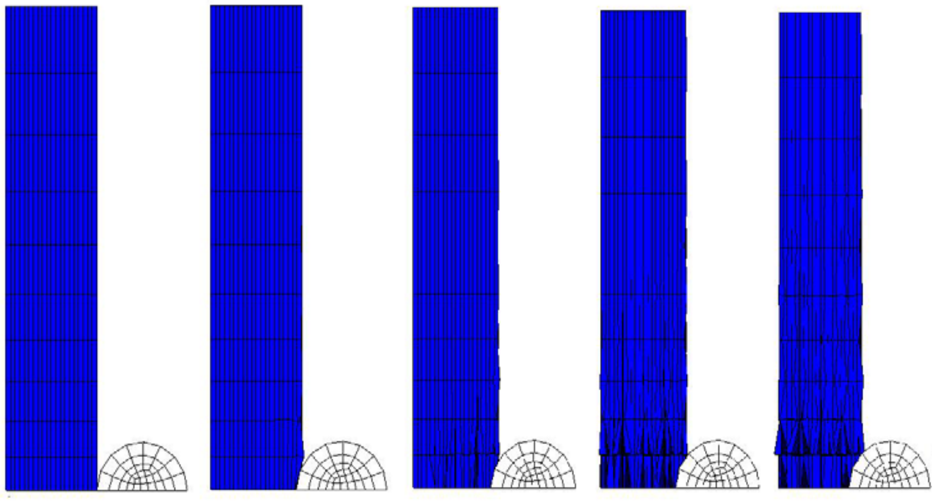

Figure 4 Delamination development in UHMW PE laminate

Further, it is seen in the simulations that the elements closest to the impact point fail first, see figure 4. This indicates the failure of the fibre near the impact point, which is also seen in experiments. The simulation is quite successful in describing the fracture development. The next step is to validate the models on strength.

In first instance, cohesive zones are used to simulate delamination development due to projectile impact in UHMW-PE laminates correctly. Because the cohesive zones make use of relatively simple constitutive models, other laminates can also be modelled by applying minor modifications. When the matrix-fibre system is for example changed, the surface energies change, see [5]. This can easily be implemented by adjusting the fibre properties and the properties for the cohesive elements.

CONCLUSIONS

Modelling delamination phenomena using cohesive zone techniques gives more in-depth knowledge about the delamination process. It also gives opportunities for modelling other.

Using cohesive elements, the delamination process from fracture initiation till development and failure can be described. Because the discretisation is on a layer level, details on fibre failure cannot be visualised. However, it can be said that modelling delamination using cohesive zone techniques gives more realistic results than previously. This is not only because the modelling level is on a smaller scale, but also because the uncoupling of fibre properties and adhesive properties gives a more physically correct description of the problem.

FUTURE WORK

Using cohesive elements to predict the delamination development in laminates under projectile impact gives a more realistic idea of what occurs in the laminate during the delamination process. However, the values of the material properties of the cohesive elements are educated guesses at the moment. A reliable method to determine the material values of the adhesion between different laminate layers that gives reproducible results is required and will be developed in the future. This method should preferably be a dynamic one, because of the dynamic loads that are encountered by the laminate. After this, the model should be validated for strength predictions.

Besides the requirement for determining the material properties for the cohesive elements, more experiments on post impact analysis are required in order to determine the exact location of failure of the layers due to projectile impact. When it is possible to determine this, a better estimate of the dicretisation size of a laminate is possible.

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