Development of a new finite element for composite delamination analysis

E. ABDULLAH*, J.-F. FERRERO**, J.-B. MOUILLET***, J.-J. BARRAU**

*IGM - ENSAE - LMS-, 10 avenue Edouard Belin, 31055 TOULOUSE Cedex 4, FRANCE
**IGM - UPS - LGMT, 118 Rte de Narbonne, Bât. 3R1, 31062 TOULOUSE Cedex, FRANCE
***Mecalog / Eurosim Toulouse, 42 Av du Général De Croutte, 31100 TOULOUSE, FRANCE

Abstract

A new solid hexahedron element for composite delamination analysis is introduced. The 8-node solid is derived from a 20-node hexahedron element and has three translational and three rotational degrees of freedom. The particularity of this new element is its aptitude to be transformed into two physically independent 4-node shell elements. This separation into two shells is governed by a delamination criterion. Thus, the decrease in mechanical properties due to delamination, i.e. bending stiffness and buckling resistance, is correctly represented independently of the membrane stiffness which, in some cases, might stay intact. This element will be essentially used to model damages on structures like helicopter blades and sinus-wave crash absorber beams. The actual classical modelling of such complex structures is onerous. The new element will allow to simplify models and decrease the calculation time. Experimental tests are carried out on composite structures such as Double Cantilever Beam specimens. The DCB test is modelled using the new element. A critical energy release rate criterion is used to govern the delamination propagation. The numerical simulation correlate well with the experimental results.

1. Introduction

The use of composite materials has become widespread in the industry. Crash and impact on full-scale test articles is very expensive, therefore it is necessary to develop accurate numerical models to replace costly tests. Thus, it is important to correctly simulate the damage phenomena experienced by the composite materials. However, the modelling of industrial composite structures damages, especially delamination, remains a hard task and requires a high computation time.
In the present paper, a new way is proposed to model composite delamination that allow to simplify complex models. A new element is introduced especially developed for composite delamination analysis.

2. Limitation of actual models

There are two essential methods for composite delamination FE modelling. The first method consist in using one layer of solid elements per composite ply [1] eventually linked together by interface elements [2, 3]. This method is expensive in CPU time and becomes laborious as the structure to model becomes complex.

The second method consist in using one multi-layered shell element through the laminate thickness [4, 5, 6]. This element has no access to the transverse normal stress σ_{33}. Hence, it is not able to delaminate in mode I.

Delamination has direct influence on bending stiffness and buckling resistance. In fact, delamination can be described as layers separation that locally decreases the moment of inertia of the structure. Yet, delamination is sometimes modelled by reducing the element material properties (E, G, ν) which essentially affects the membrane stiffness of the structure while the bending stiffness may be barely altered.

3. The proposed solution

The proposed solution consist in using one multi-layered 8-node solid element through the laminate thickness which has access to the transverse normal stress and, therefore, able to delaminate in mode I.

First, a simplified representation of damage mechanisms is defined : only one delamination in mode I occurs through the thickness. It is governed by σ_{33} stress. Once this separation takes place, the σ_{33} stress present in the two newly formed parts at each side of the crack are insufficient to produce another mode I crack opening. Nevertheless, these two parts may experience important shear stresses and bending moments that cause damages such as matrix cracking, fibre rupture and mode II or III delamination.

Since, in an already delaminated element, the σ_{33} stress have no physical use in the two laminates that appear at each side of the crack, the initial 3D solid element might behave, after delamination, as two physically independent shell elements. Thus, the decrease of the local moment of inertia and, consequently, of the bending stiffness and buckling resistance are correctly represented independently of the membrane stiffness which, in some cases, might stay intact.

In other words, a new 3D solid element is proposed in this paper that is able, once it experiences delamination, to be transformed into two separate shells. This allow to simplify the modelling of industrial composite structure and to describe correctly the delamination phenomenon.

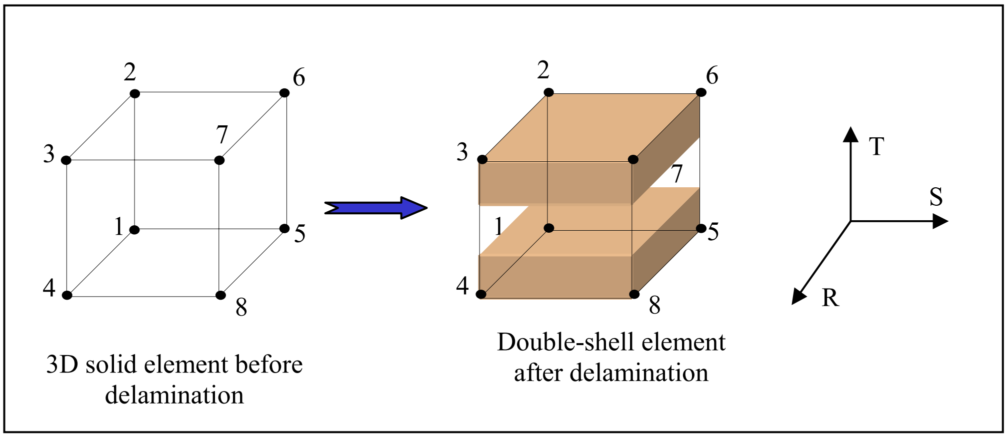


Fig. 1. Transformation of the 3D solid element into a double-shell element

4. Development of the new element

The 8-node solid element is derived from a 20-node hexahedron element as described by Yunus et al [7], and has three translational and three rotational degrees of freedom. The transformation is done by giving the instantaneous velocity of the mid-side node as a function of the corner nodes velocities :

$$u_k = \frac{1}{2}(u_i + u_j) + \frac{z_j - z_i}{8}(\omega_{yi} - \omega_{yj}) + \frac{y_j - y_i}{8}(\omega_{zj} - \omega_{zi})$$
$$v_k = \frac{1}{2}(v_i + v_j) + \frac{z_j - z_i}{8}(\omega_{xj} - \omega_{xi}) + \frac{x_j - x_i}{8}(\omega_{zi} - \omega_{zj})$$
$$w_k = \frac{1}{2}(w_i + w_j) + \frac{x_j - x_i}{8}(\omega_{yj} - \omega_{yi}) + \frac{y_j - y_i}{8}(\omega_{xi} - \omega_{xj})$$

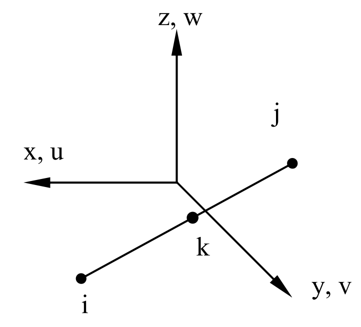


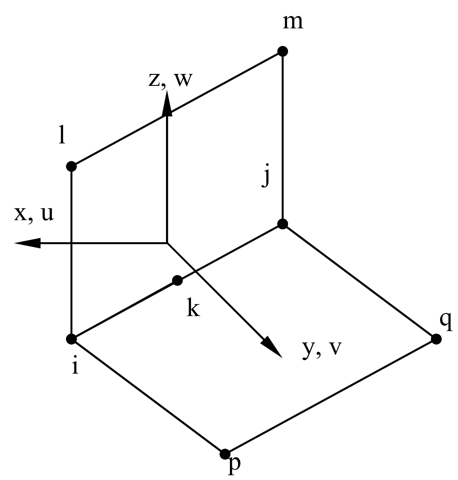
Fig. 2. A typical element edge

This transformation does not allow the mid-side node to move along the edge. Looking at the transformation equation above, it can be seen that the mid-side node is constrained to stay at the middle of the edge between the corner nodes.

This restriction seems to stiffen the bending behaviour of the element. In fact, the analytical solution of a beam under constant moment [8] shows that the mid-side points move along the side edges.

In order to correct the translation motion along the edges, a modified velocity transformation is proposed that enables the mid-side node to leave the halfway position in function of the corner nodes rotations :

$$u_k = \frac{1}{2}(u_i + u_j) + \frac{z_j - z_i}{8}(\omega_{yi} - \omega_{yj}) + \frac{y_j - y_i}{8}(\omega_{zj} - \omega_{zi})$$
$$+ \frac{1}{4}\frac{x_j - x_i}{8}\left(\omega_{yi} + \omega_{yj} - \omega_{yl} - \omega_{ym} - \omega_{zj} - \omega_{zi} + \omega_{zp} + \omega_{zq}\right)$$
$$v_k = \frac{1}{2}(v_i + v_j) + \frac{z_j - z_i}{8}(\omega_{xj} - \omega_{xi}) + \frac{x_j - x_i}{8}(\omega_{zi} - \omega_{zj})$$
$$+ \frac{1}{4}\frac{y_j - y_i}{8}\left(-\omega_{xi} - \omega_{xj} + \omega_{xl} + \omega_{xm} + \omega_{zj} + \omega_{zi} - \omega_{zp} - \omega_{zq}\right)$$
$$w_k = \frac{1}{2}(w_i + w_j) + \frac{x_j - x_i}{8}(\omega_{yj} - \omega_{yi}) + \frac{y_j - y_i}{8}(\omega_{xi} - \omega_{xj})$$
$$+ \frac{1}{4}\frac{z_j - z_i}{8}\left(\omega_{yi} + \omega_{yj} - \omega_{yl} - \omega_{ym} + \omega_{xi} + \omega_{xp} - \omega_{xj} - \omega_{xq}\right)$$



Thus, the translation along the sides follows the normal motion of the upper and lower edges.

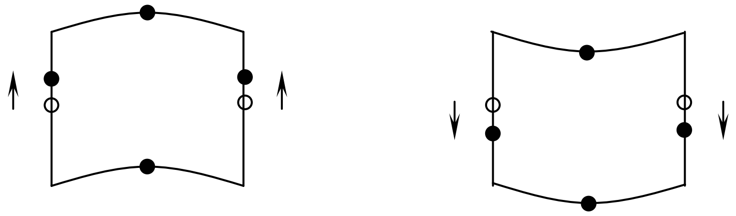
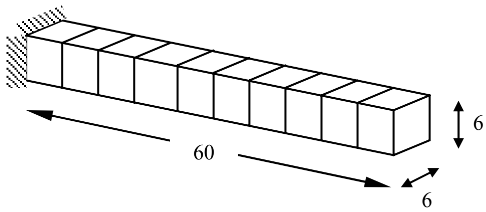


Fig. 3. Translation motion along the edge relative to the normal motion of the edge

In order to validate these modifications, simulations of a bending beam are carried out using the new element created with the old transformation, the new element with the modified transformation and classical brick elements as shown below.



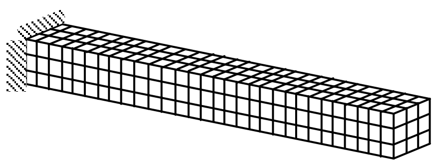
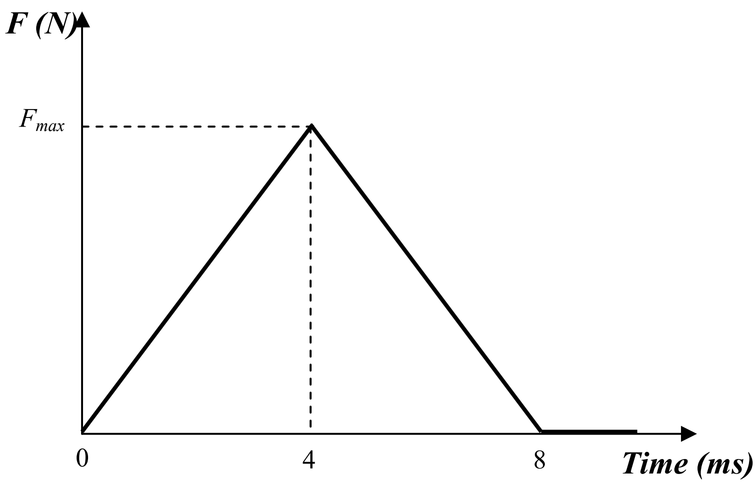


Fig. 4. Model A. using the former and the modified element Model B. using brick elements

An explicit finite element code is developed in Fortran language in order to carry out simulations using the new element, model A in this case. Model B is simulated using the explicit finite element code RADIOSS.

The material properties used are those of steel : $\rho = 0.0078$ g/mm^3, $E = 210000$ MPa, $\nu = 0.3$.
The total force applied on the beam free end varies as follows :



Results show that the old transformation gives a stiff behaviour compared to the analytical static solution and RADIOSS result. The modified transformation curve is closer to the RADIOSS curve and oscillates around the static solution.

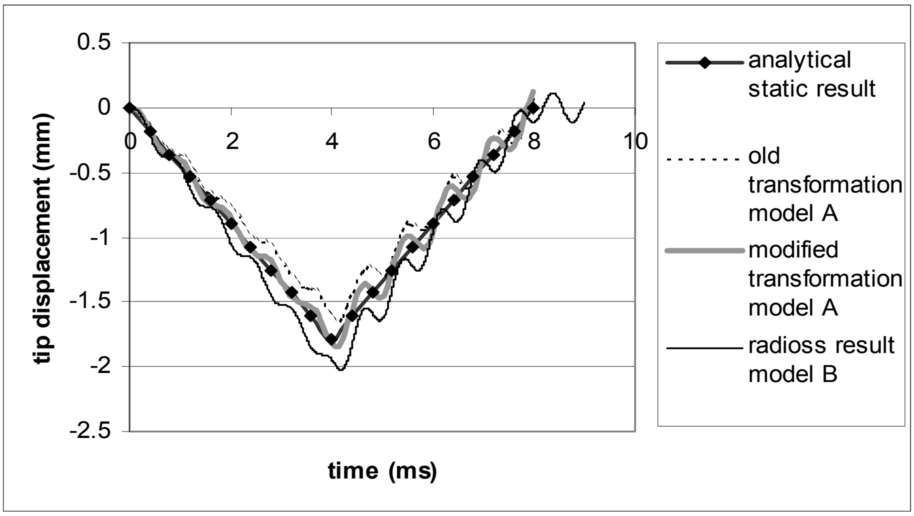


Fig. 5. Tip displacement with respect to time

This element has the advantage that shell nodes can be shared with brick nodes. Note that the faces have just 4 nodes which is favourable for the contact-impact computation time.

This element is integrated with 4 points per layer. Each layer corresponds to a composite ply of the laminate and has the material properties of this ply.

The separation into two shells is governed by a delamination criterion. The place where the delamination occurs through the thickness can be predefined by the user by giving the thickness' of the two post-delamination shells. This element will be essentially used to model damages on structures like helicopter blades and sinus-wave crash absorber beams. The predefined delamination zone can, for example, correspond to the location of the triggers in the sinus-wave beams.

The coupling of solids and shells is studied. A double cantilever beam simulation was realised with two different models : the first consist in 5 new solid elements coupled with 5 shell elements while the second consist in brick elements as shown on the figure below.

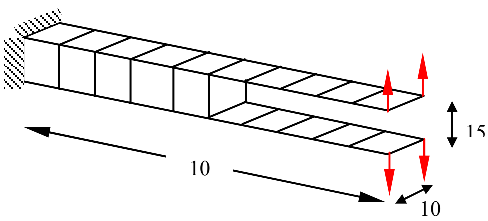
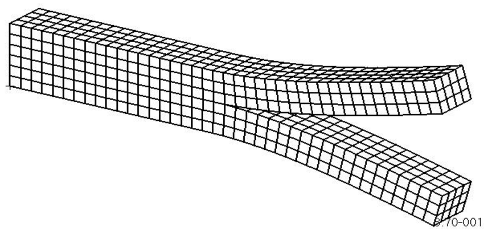


Fig. 6. Model A. using the new element coupled with shells



Model B. using classical brick elements

The tip displacement obtained with model A using an explicit finite element code is compared to the RADIOSS (none linear explicit FE code) and FE code SAMCEF (none linear implicit FE code) results using model B.

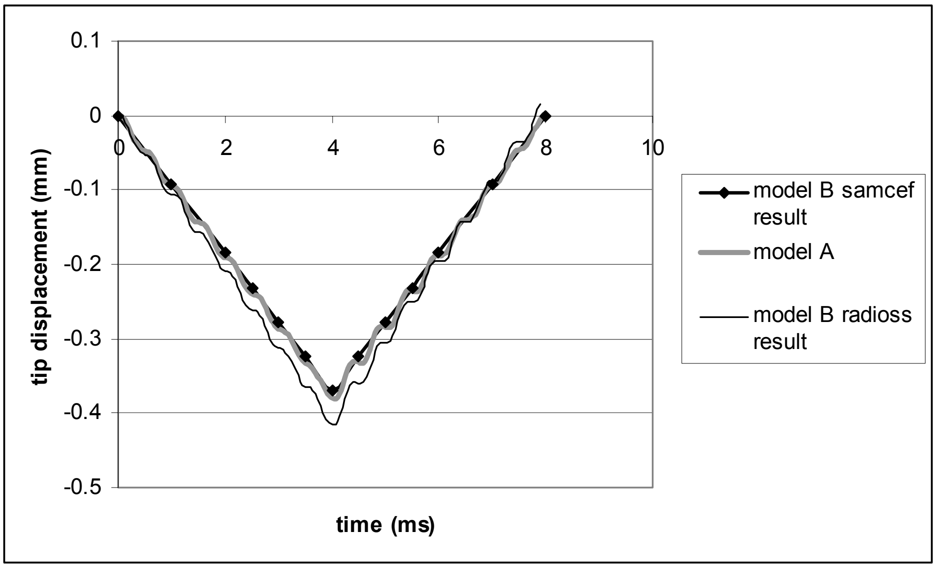


Fig. 7. tip displacement with respect to time

The two models, A and B, give coherent results and thus show a good coupling between the new solid element and shell elements.

5. Experimental test and numerical simulation

An experimental test is carried out on a Double Cantilever Beam (DCB) specimen. The beam dimensions in millimetres are 200 × 20 × 5.52. The materials chosen are pre-impregnated bi-directional (G803/914) and pre-impregnated unidirectional (T300/914) carbon fibre laminae. The stacking sequence is :

8 plies of G803/914 at 0°
4 plies of T300/914 at 90°
8 plies of G803/914 at 0°

The beam has a 30 mm long initially delaminated zone on one G803/914-T300/914 interface. The value of the critical energy release rate is found experimentally to be 700 J/m².

The beam was modelled with one element along the thickness and depth, and 20 elements through the length.

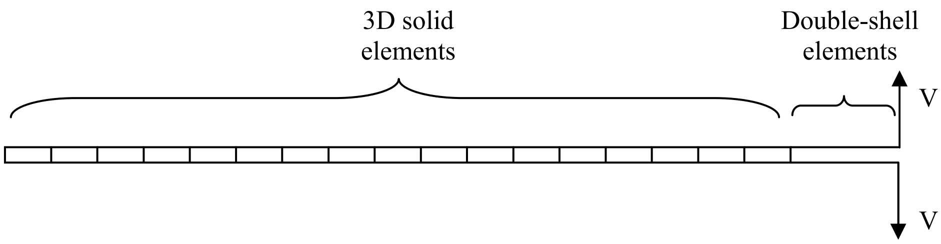


Fig. 8. FE model

In order to eliminate zero energy deformation modes, full integration (9 point Gauss integration rule) in each ply is used.

Constant velocity is applied at the beam tip nodes.

5.1 Delamination criterion

For the DCB case, the energy release rate can be computed as :

$$G = \frac{3}{2}\frac{F \times \delta}{a \times b}$$

where F is the force at the loaded nodes, δ is the distance between the upper and lower nodes of the loaded beam tip, a is the total crack length and b is the beam width.
The crack propagation velocity is taken as :

$$\dot{a} = \omega \times C \times \Delta G$$

where C is the sound propagation speed in the material, and ω is a damping factor.
When G reaches the critical energy release rate G_c the delamination length increases by $\dot{a} \times \Delta t$, where Δt is the time step. $\Delta G = G - G_c$ and corresponds to the energy accumulated in the structure during a time step.

5.2 Damage law

The element can experience 3 different states : volume state where no delamination has yet been detected, double-shell state where the delamination has totally crossed the element, and hybrid state where delamination is still propagating within the element.
The crack propagation inside the element can be represented as a local loss in transverse properties (E_{33}, G_{13}, G_{23}). A damage parameter d is thus introduced that varies as a function of crack length : d is equal 1 when there is no delamination, and d is equal 0 when the crack length is equal to the element length. All of the transverse properties are assumed to decrease in the same way, and therefore are affected by the same damage parameter.
A finite element analysis is carried out in order to determine the variation of the transverse mechanical properties with respect to crack length. A finely meshed model with an initial crack and a coarsely meshed model without crack are considered. A parametric study with different initial crack lengths is realised to compute the equivalent E_{33} module in the coarsely meshed model that allows to give the same tip displacement for the same loading as the finely meshed model.

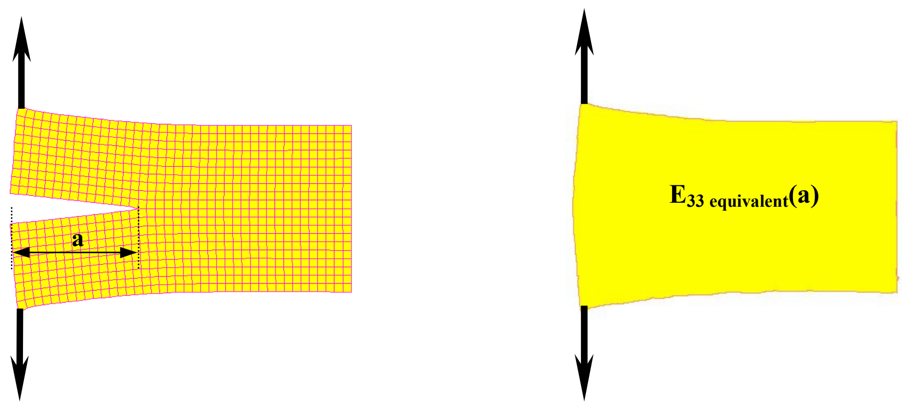


Fig. 9. Models considered to compute the variation of E_{33} as a function of the crack length

The curve that was found to represent well this variation is hyperbolic as shown on the figure below :

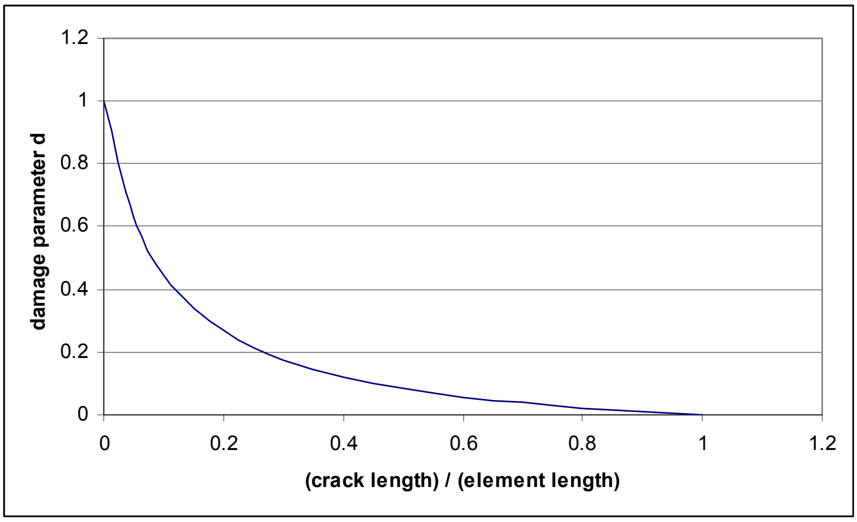


Fig. 10. Damage law as a function of crack length

5.3 Transfer law

In parallel to the damage parameter which affects the transverse mechanical properties of the element, a transfer law is also introduced that governs the transition between the initial volume element and the final double-shell element. For the present DCB case, no damages are considered to occur in the two beams portions at each side of the crack. the in-plane stiffness of the structure is assumed to remain constant. Thus, the transfer is done, on the one hand, by reducing gradually the in-plane mechanical properties of the 3D solid element and on the other hand by increasing the shell properties so as the resulting in-plane stiffness remains unchanged. The transfer parameter d_{transf} is also taken as a function of the crack length : it is equal to 1 when there is no delamination, and 0 when the crack has the same length as the element. d_{transf} multiplies the solid in-plane mechanical properties while $(1-d_{transf})$ multiplies the shell properties. The variation of d_{transf} and $(1-d_{transf})$ versus the crack length is as follows :

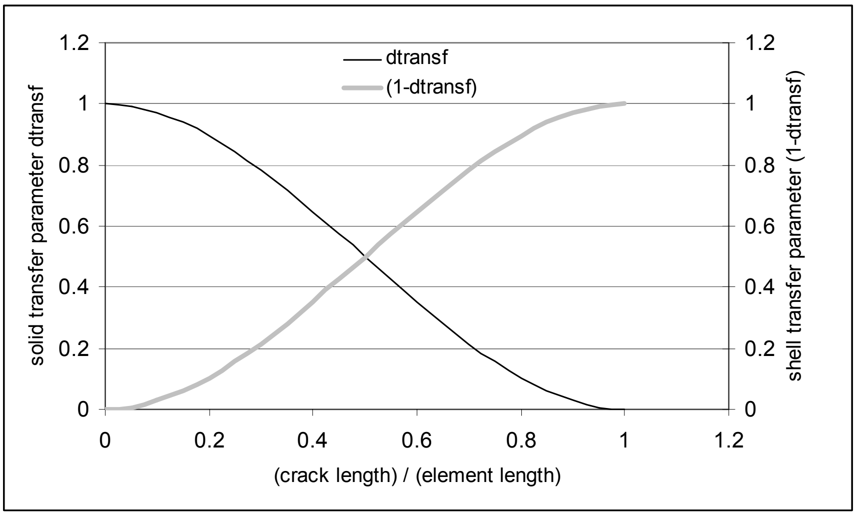


Fig. 11. Transfer law as a function of crack length

6. Results and discussion

Figure 12 shows the resultant force at the beam end where the displacement is imposed as a function of the tip displacement. The simulation shows a good result. The transition between the solid state and the double shell state occurs smoothly without any brutal vibrations. The damage law representing the crack propagation inside the element seems to correspond well to the real delamination propagation inside the structure.

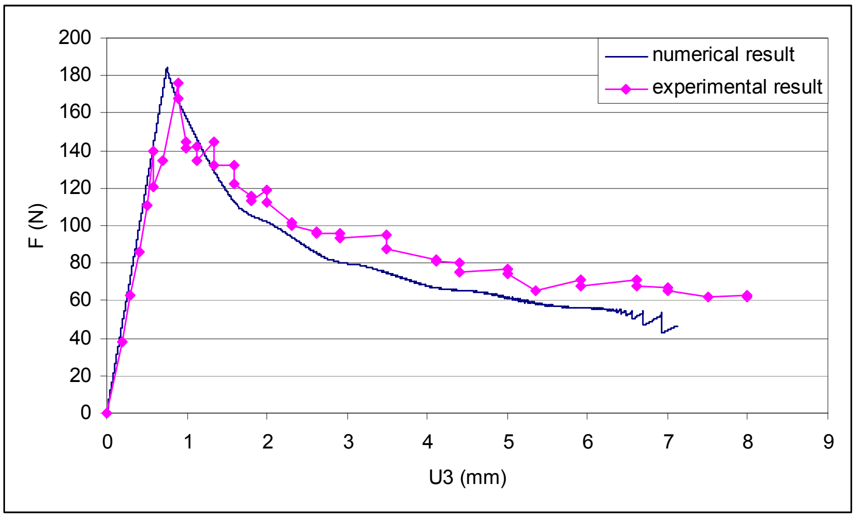


Fig. 12. Comparison between experiment and simulation

7. Conclusion and Perspectives

A new 3D multi-layered element for composite delamination analysis has been presented. The element transforms into two independent shells as it experiences delamination. The modelling of composite structures delamination requires the use of a low number of this element and models can become less complex. The 3D solid element introduced by Yunus et al was modified and validated. The coupling between this solid element and shell elements was also validated. The numerical procedure of the transformation from the 3D element to the double-shell element does not present any computing troubles. Crack propagation inside the element can be well represented by a damage law that affects the transverse mechanical properties. Thus, relatively coarse mesh may be used for composite damage analysis. The delamination criterion used so far is the critical energy release rate computed over the structure. Such criterion can only be used for the particular case of Double Cantilever Beam. The next step is the elaboration of a delamination criterion at the element level which can be used in a general way.

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