

Advanced Decohesion Elements for the Simulation of Composite Delamination

Charles C. Rankin, Marc Regelbrugge, and Bryan Hurlbut

All authors from Rhombus Consultants Group, Inc.

Abstract: This paper introduces an alternative decohesion element that offers improved convergence characteristics over other formulations. The new element's implementation as an Abaqus UEL is discussed, along with certain insights the authors have developed that illuminate at least some of the factors complicating convergence of cohesive-element models. Methods for improving convergence of delamination and disbond problems are presented and evaluated with respect to a canonical test case.

Keywords: Delamination, decohesion, UEL, traction-separation, traction, non-symmetry, convergence.

1. Introduction

Delaminations compromise the integrity of high-performance composite structures and are costly to locate, characterize and repair. Structural design and analysis can help to ensure composite structural durability, but modeling is often complicated by poor knowledge of local material behavior and inherent coupling of geometric and material fracture nonlinearities in damaged or failing structures. In addition, even with a verified model, convergence to each nonlinear solution may be very difficult to achieve, resulting in failed solutions and much higher costs.

One powerful modeling tool for simulating delamination progression is the so-called *decohesion* element, or *cohesive* element. Two- and three-dimensional versions of such an element are provided in Abaqus/Standard as element types COH2D4, COHAX4, COH3D6 and COH3D8, respectively. While these elements have proven flexible and effective for many problems, they can engender difficulties for obtaining converged nonlinear solutions – particularly in mixed-mode problems that are characteristic of composite delamination occurring under bending and transverse-shear loads. For such problems, mode mixity typically changes and evolves as the delaminating surface unloads, and the decohesive process must necessarily account for such mixity if minimum-energy solutions are to be obtained.

2. Approach

Our development introduced a new decohesion element as an Abaqus UEL based on the Goyal-Johnson (GJ) (Goyal, 2003) formulation. The motivation for doing this was to provide us with detailed performance information at all levels of the implementation, including the properties of the traction-separation function that forms the physical basis for the decohesion process. Once the implementation was verified, we were able to isolate any aspects that could interfere with performance, including formulation of the tangent stiffness matrix. In this paper, we introduce the GJ cohesive UEL and discuss features that we believe improve its performance relative to other implementations.

2.1 The Goyal-Johnson UEL

Cohesive elements are interface elements that generate nodal forces based on interpolated separation displacements and tractions generated from these displacements. Figure 1 illustrates some of the features of these elements, which include the standard COH3D8.

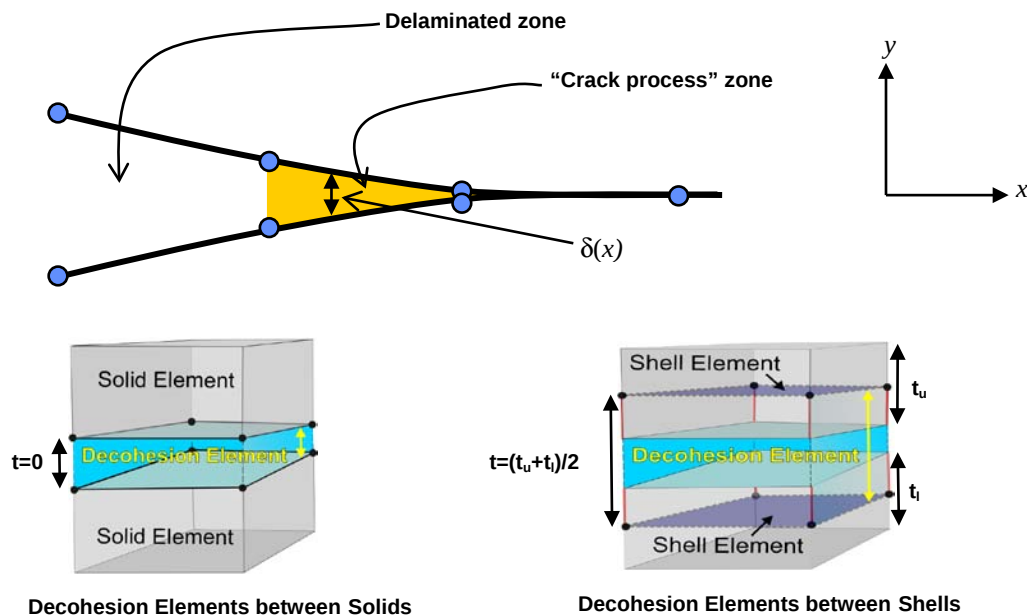


Figure 1. Illustration of cohesive geometry and properties.

The top part of the figure illustrates a very important feature of all cohesive elements: the area where the crack is forming and separating is smeared out over a region called the *process zone* where most of the work is being done to create new crack area. The bottom part of the figure illustrates the placement of the cohesive

element for solid and shell elements, respectively. The cohesive element is given a thickness for illustration purposes only; our GJ element has zero thickness. The shell element implementation accounts for the offset of the shell reference surface with the interface.

Figure 2 compares the traction-separation function of the GJ formulation and the COH3D8, see (Camanho, 2003) for a description of this element. The most important feature of all decohesion elements is that the integral of the traction-separation function must equal the critical strain energy release rate (SERR) for the fracture mode in question. Another decohesion requirement feature is to accumulate irreversible damage. This is implemented in both types of elements by a linear unloading from a post-initiation separation (illustrated in Figure 2 as a linear unloading to zero from any given point on the curve to the right of the function's maximum). This feature ensures that no “healing” can take place during the response—a fact that has important implications for the properties of the tangent stiffness matrix, and consequently, solution convergence.

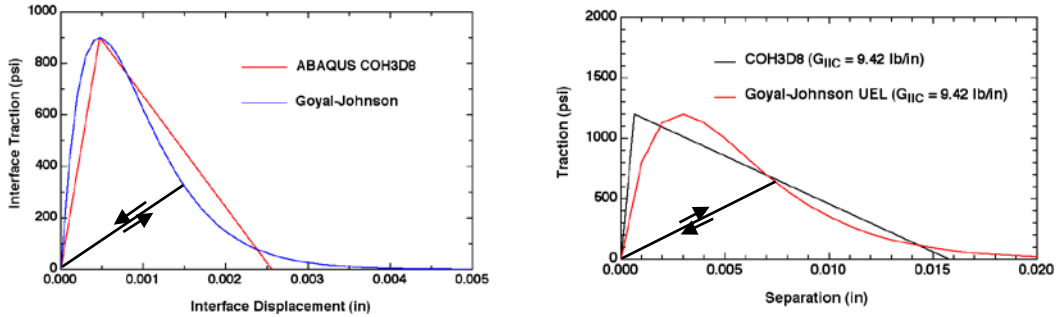


Figure 2. Traction-separation functions for the two decohesion elements.

The specific form the GJ traction-separation function we have employed is shown by the following equation.

$$\begin{aligned} \begin{Bmatrix} \bar{T}_s \\ \bar{T}_3 \end{Bmatrix} &= \begin{Bmatrix} \bar{u}_s \\ \langle \bar{u}_3 \rangle \end{Bmatrix} \exp[2 - \mu/d - d] - \begin{Bmatrix} 0 \\ \langle -\bar{u}_3 \rangle \end{Bmatrix} \exp[1 + \kappa|\bar{u}_3|] \\ \bar{T} &= T / T_c, \quad \mu = \left[|\bar{u}_s|^\alpha + \langle \bar{u}_3 \rangle^\alpha \right]^{1/\alpha} \end{aligned} \quad (1)$$

The symbols on the left hand side of Equation 1 are the normalized output tractions for the shear and normal directions, denoted by the subscripts s and 3 respectively. Variables $\bar{u}_s$ and $\bar{u}_3$ are the corresponding normalized displacements that take the value of unit at maximum of the traction-separation curve. The exponent α is for the power-law mode mixity rule

$$(G/G_C)^{\alpha/2} = (G_I/G_{IC})^{\alpha/2} + (G_{II}/G_{IIC})^{\alpha/2} \quad (2)$$

and is determined by the best fit to available test data. The critical traction (T_c) is the maximum traction value, and is related to the critical displacements by the following:

$$u_{sc} = \frac{G_{IIC}}{\psi T_{sc}}, \quad u_{3c} = \frac{G_{IC}}{\psi T_{3c}}, \quad \psi = e\Gamma[2] \quad (3)$$

It can be readily seen that the critical tractions and their corresponding critical separations are intimately related to the critical SERR in each mode. SERR values are intrinsic material properties measured by test.

The quantity d in Equation 1 is the *damage parameter* whose initial value is 1 in the pristine material. The second term on the right hand side of Equation 1 accounts for possible compression of the interface by imposing a penalty on surface contact automatically (the brackets around $\langle \bar{u}_3 \rangle$ denote the Heavyside function that takes on the value of the enclosed argument when positive, and is zero when the argument is negative).

Several important advantages accrue from the GJ formulation. First, there is a simple analytical connection between the critical tractions, the critical separations, and the critical SERR. Second, the response function is continuous for all branches, including the unloading portion involving progressive failure. Third, the tangent stiffness can be computed by a straightforward differentiation of Equation 1. We note that differentiation of Equation 1 generally yields an unsymmetric tangent stiffness in mixed-mode cases where normalized separations in both fracture modes are nonzero and not necessarily correlated. As such, we compute all terms consistently, and provide the entire, possibly unsymmetric, stiffness matrix as output from the GJ UEL.

Our GJ UEL was implemented with two available interpolaton orders: an 8-node linear interpolation and an 18-node Lagrange-interpolated quadric version. Displacement interpolation, energy integration and formulation of the element stiffness matrix and nodal forces are standard finite-element processes that are not covered here.

3. Goyal-Johnson Element Verification

3.1 DCB element verification

The UEL-implemented GJ element was verified by comparison with the COH3D8 Abaqus element and a GJ element implemented in the STAGS code. Figure 3 shows results of this comparison.

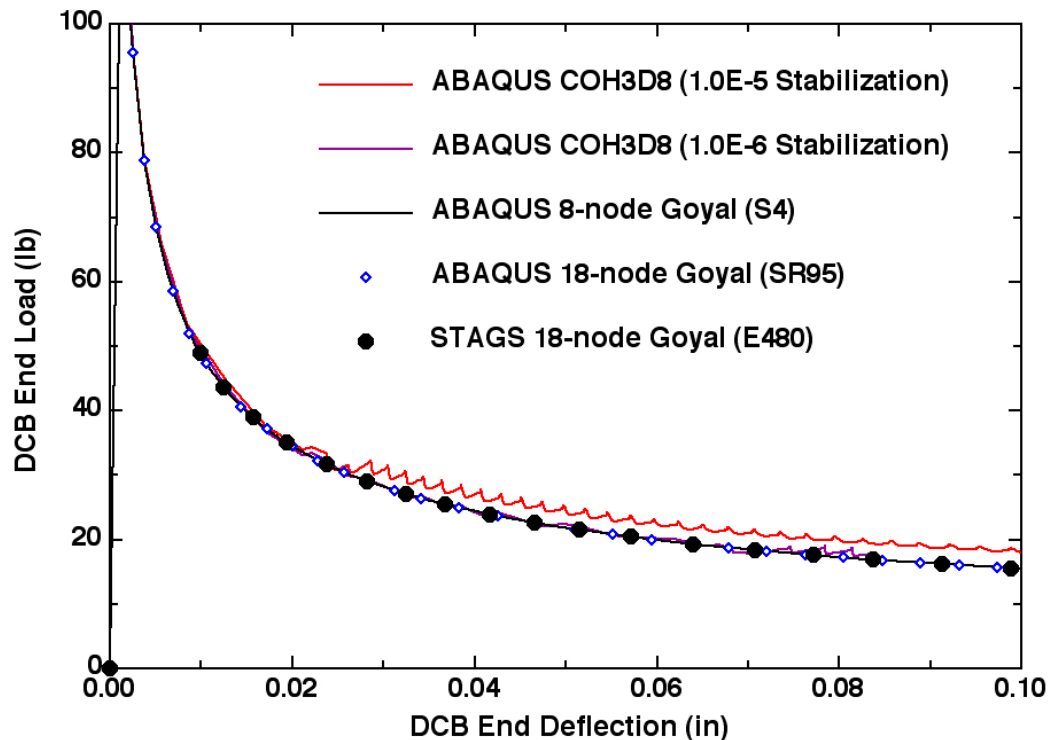


Figure 3. DCB comparison of GJ UEL with COH3D8.

The reader will notice the strong agreement between COH3D8 and the GJ UEL models. The STAGS model also agrees well with the Abaqus models. However, Figure 3 also provides a hint of convergence difficulties, because in order to simulate even this simple double-cantilevered beam test case, we required a small stabilization parameter to get converged solutions with the Abaqus element. The danger of requiring stabilization is evident from the sensitivity of the solution to the value of the stabilization (artificial damping) parameter required for stabilization.

Apart from the use of stabilization for the Abaqus element, convergence was not problematic for the DCB test case. The GJ UEL converged quadratically as

viewed from the Abaqus iteration history, indicating that the tangent stiffness was consistent with traction-separation function in Equation 1. It turns out that for this particular problem dominated by a single crack extension mode I, the traction-separation problem for the GJ element can be derived from a potential energy functional. Thus, the tangent stiffness is symmetric. It appears that the improvement of the GJ convergence and solution properties over the COH3D8 may, in part, be due to the smooth nature of the GJ traction-separation function in Equation 1.

3.2 Mixed-mode example problem

Our next task was to try out a more difficult problem that involves a mixed-mode response. The example problem shown in Figure 4 fits the bill perfectly.

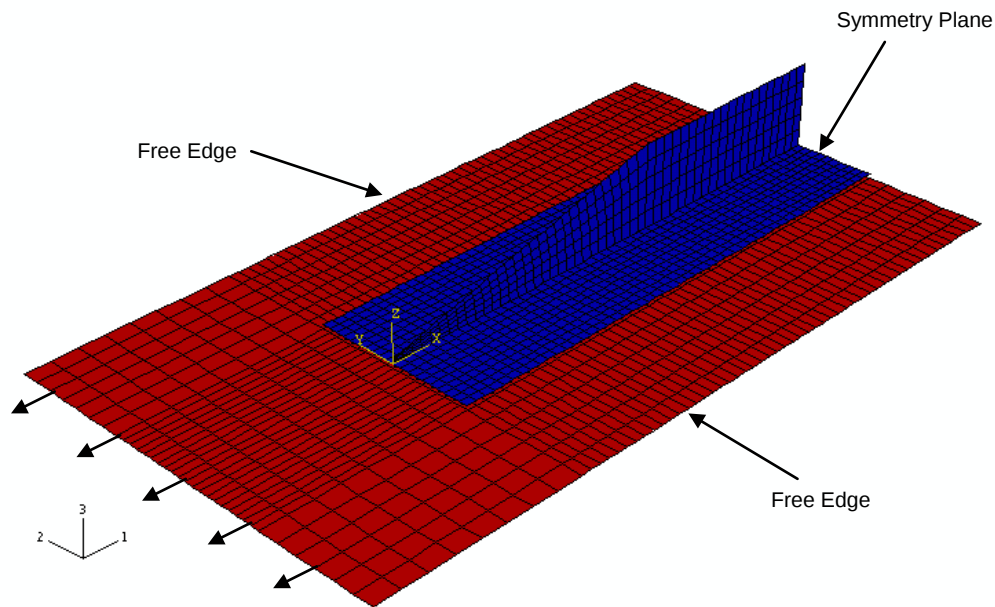


Figure 4. Mixed-mode example problem configuration.

Our symmetric test-case model contains all the essential ingredients to simulate response of a generic stiffener termination under tensile loading. In this model, a 45 degree ply in the stiffener is adjacent to the skin, so a mixed-mode response is expected which is asymmetric with respect to the plane of the stiffener blade. The mode mixity rule is shown in Equation 2 above.

When we initially ran both the GJ UEL and COH3D8 elements in the example problem, we encountered so much convergence difficulty that we were unable to obtain a solution, except with very high stabilization-parameter values. We tried a variety of Abaqus/Standard solution strategies with little benefit. With the unsymmetric stiffness option, however, we immediately regained the quadratic convergence that we had seen for the DCB case using the GJ element. In this example case, it appeared that preserving lack of symmetry in the decohesion-element stiffness matrix was critical for convergence.

To see why this behavior should be anticipated, we examined more closely the tangent stiffness for the mixed mode case in Equation 1. It becomes immediately clear that once tractions are established for a system whose critical SERR's differ for shear and normal displacement, the resulting tangent stiffness is decidedly non-symmetric. This property is exaggerated for a typical composite system since the critical SERR for shear is often an order of magnitude greater than that for mode I cracking. Therefore, one would expect convergence difficulties when a symmetric solver is used in mixed-mode cases. In contrast, the unsymmetric option in Abaqus provides a very simple way to overcome this difficulty: not only could we establish the consistency of our stiffness formulation, but also we could demonstrate conclusively that the resulting consistent stiffness yields the proper quadric convergence to solution. A snapshot of the solution using the GJ element is shown in Figure 5.

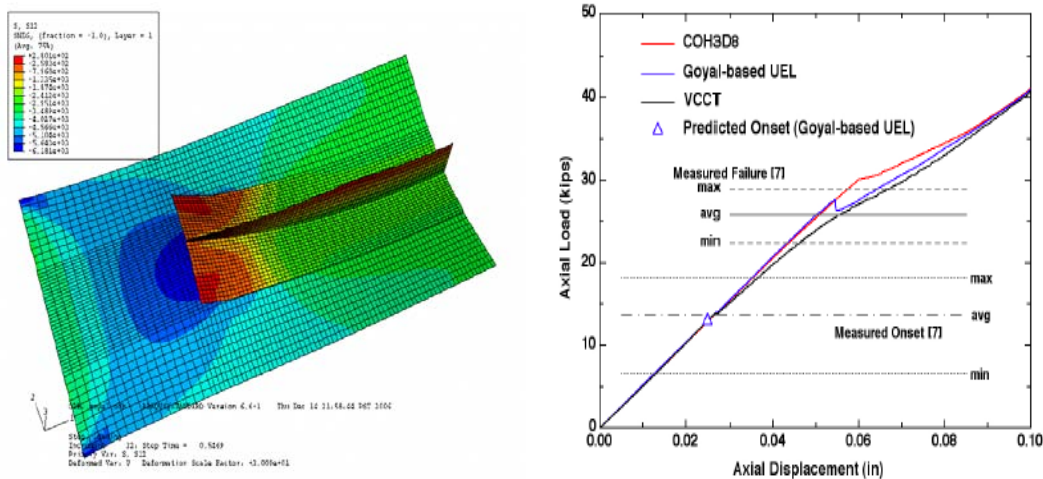


Figure 5. Solution of the mixed-mode example problem.

The reader will note the slight sideways motion of the stiffener termination, showing the changing environment at the delamination front as the solution

evolves. The plot on the right compares the two elements; one will note that the very high value of stabilization for the COH3D8 affected the predicted axial failure load (we were not able to get any solution for lower stabilization constants).

The right-hand plot in Figure 5 also includes an Abaqus VCCT solution of the example problem. Convergence is smooth in the VCCT solution, although VCCT predicts a greater loss of panel stiffness after onset of the delamination than either cohesive-element model.

4. The necessity of the unsymmetric stiffness matrix

One might ask if it is possible to reformulate the GJ UEL so that the tractions can be derived from a potential energy function. If that could be done, the tractions would be independent of the solution path and the tangent stiffness would be symmetric. Such independence would reveal itself through the Maxwell reciprocity relationship

$$\frac{\partial T_3}{\partial \mu_s} = \frac{\partial T_s}{\partial \mu_3} \quad (4)$$

Equation 4 states that the gradient of the mode I traction with respect to the shear is equal to the gradient of the shear traction with respect to the normal displacement. If a potential exists, Equation 4 can be proven easily. Conversely, one can easily show that for a dissipative system such as this one, path independence cannot exist because the traction must disappear if *either* the shear or normal displacement becomes large. The next figure illustrates this case:

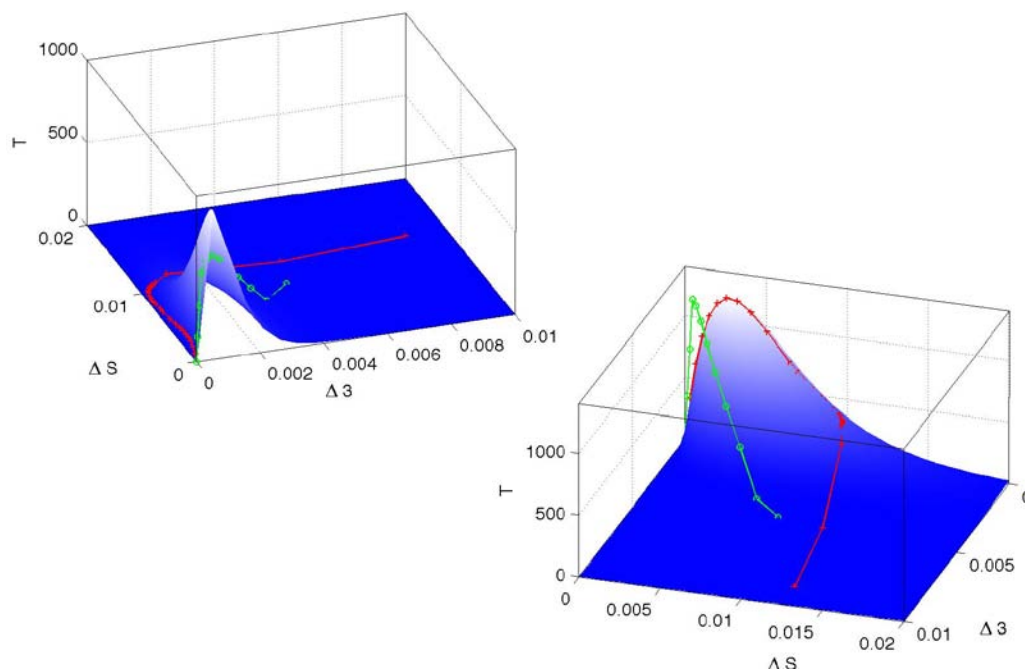


Figure 6. Illustration of the dependence of the tractions on the solution path.

The figure on the top left shows the normal traction as a function of the two normalized displacements (shear and normal). The bottom right figure shows the shear traction. Note first of all that the shear traction is much greater than the normal traction, a clear reflection of the greater critical SERR for shear. One can see also that the tractions vanish (as they must) for large values of either displacement variable. The curves denote data taken directly from an Abaqus execution for an element near the corner of the stiffener flange. The red curve is for the GJ element, where the reader can see that the path is a sensitive function of the response. It is also evident that the solution must be dependent on the path, given the constraints imposed on the traction-separation function. The solution path we obtained for this problem using the COH3D8 element is shown by the green line. When we switched to the unsymmetric solver for the COH3D8 run, there was very little change in the solution behavior as compared with the same element using the standard symmetric solver

4.1 Detailed performance metrics

Figure 7 illustrates the efficiency of the solution process for the various example case strategies:

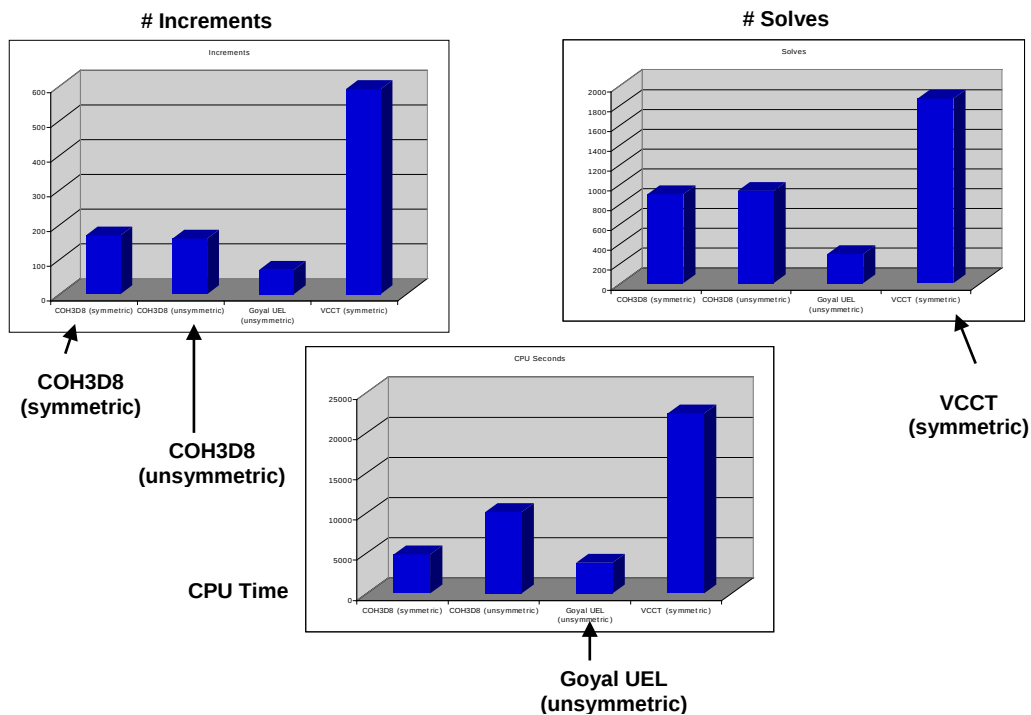


Figure 7. Performance Metrics for Example Case using GJ UEL, COH3D8 and VCCT.

The bars in the graphics are labeled with the element and solution strategy chosen; this same order is maintained in each graphic. It is quite clear that even with the near two-to-one penalty for using the unsymmetric solver, the reduced number of increments for the GJ element more than offsets that cost. This is all the more important because it was not necessary to use stabilization for this element.

5. Conclusions: Strategies for improving performance

The small study described above has illuminated some important issues for predicting and simulating onset and propagation of interlaminar fracture in composite structures. First and foremost, while the successful approaches (including cohesive elements and the VCCT procedure) are all based on the energetics of the evolving fracture surface, they incorporate diverse criteria for evaluation of mixed-mode fracture energies. The present work was not focused on development of mixed-mode models, but the GJ formulation does admit derivation of a consistent, albeit generally unsymmetric tangent stiffness matrix. We have seen that the incremental cohesive-interface stiffness is generally

unsymmetric in the mixed-mode case, and that the unsymmetric consistent tangent derived for the GJ model allowed quadratic convergence of the Newton iterations in the mixed-mode example problem. Solution times for the unsymmetric GJ model were very competitive with the COH3D8 model, which used Abaqus' symmetric solver, owing to a drastically reduced number of iterations required for the GJ solutions.

Second, our experience with these cases has led us to believe that convergence of the cohesive models is enhanced by the relative smoothness of the GJ constitutive law. The GJ traction-separation function is continuously differentiable, so the solver need not work through jump-type stiffness discontinuities. While Abaqus' solver features many techniques for enhancing convergence of discontinuous solutions (including the stabilization parameter), we found we did not have to employ these options to obtain good solutions with the GJ elements.

Finally, from a modeling perspective, we appreciate the flexibility afforded by the Abaqus UEL to implement a zero-thickness cohesive element. We found the process of incorporating these elements into both solid- and shell-type models to be straightforward, requiring only duplicate nodes on chosen interfaces without adjusting the models' through-thickness geometries.

Given the difficulties uncovered by this investigation, what can be done to improve the behavior of all cohesive elements? There are many reasons for less than optimum convergence behavior, including a lack of consistency of the stiffness matrix with internal force computation. In our element, we made every attempt to include all nonlinear terms, no matter how insignificant they appeared at first glance. Such attention to detail paid off handsomely for our Goyal-Johnson UEL implementation.

6. References

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7. Table of symbols

T	Interfacial Traction
T_c	Critical Interfacial Traction

$\bar{T}_s$	Shear (Mode II) traction normalized by critical shear traction
$\bar{T}_3$	Surface-normal (Mode I) traction normalized by critical surface-normal traction
$\bar{u}_s$	Shear separation normalized by critical shear separation
$\bar{u}_3$	Surface-normal separation normalized by critical surface-normal separation
u_{sc}	Critical shear separation
u_{3c}	Critical surface-normal separation
α	Exponent for power-law mode mixity rule
μ	Effective non-dimensional separation: $\mu = \left[\left \bar{u}_s \right ^\alpha + \left\langle \bar{u}_3 \right\rangle^\alpha \right]^{1/\alpha}$
d	Damage parameter (1= no damage, ∞ = complete damage)
κ	Penalty stiffness parameter for normal interpenetration
G_I	Mode I Strain Energy Release Rate (SERR)
G_{IC}	Mode I critical SERR
G_{II}	Mode II SERR
G_{IIC}	Mode II critical SERR