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Implementation of a state-of-the-art cohesive zone element for ANSYS Mechanical

J. Glud[1], E. T. Christensen[1], E. Lindgaard[1], and B. L. V. Bak[1]

(1)Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstraede 16, 9220 Aalborg Oest, Denmark, jag@m-tech.aau.dk

Summary. This paper describes the implementation and verification of a state-of-the-art user programmed cohesive zone element in the commercial finite element package ANSYS Mechanical. The user programmed element is benchmarked against the Ansys Mechanical cohesive element, INTER205. Convergence rates are better than INTER205 by 15% to 100% and extra possibilities regarding data output have been added. A standard practice to overcome convergence difficulties when using a coarse mesh with cohesive zone elements is to lower the onset traction. A study is presented which demonstrates that this practice may lead to underestimated load carrying capability.

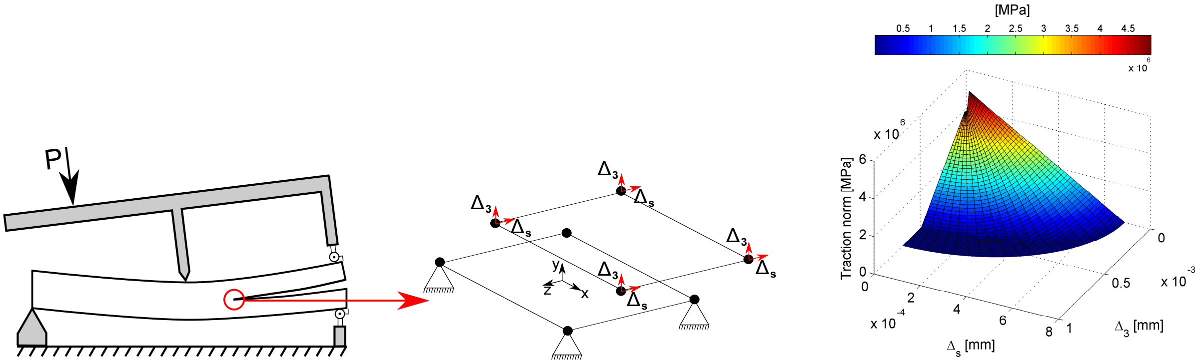
Key words: cohesive zone modelling, composite structures, user programmed, ANSYS Mechanical, finite element, fracture mechanics.

Introduction

The work presented in this paper is a part of the master thesis project [1]. The master thesis treats the formulation of a cohesive zone finite element and analyses of wrinkle defects using cohesive zone elements. The master thesis was carried out in collaboration with Siemens Wind Power A/S. Siemens Wind Power A/S manufactures wind turbine blades made of glass-epoxy-balsa laminates and the entire blade is cast in a single process using vacuum assisted resin transfer moulding. In the infusion process of large glass-epoxy-balsa composite structures, such as wind turbine blades, several types of manufacturing defects can arise [3]. Among these manufacturing artifacts are wrinkle defects. Wrinkle defects are out-of-plane fiber misaligments, which might initiate delaminations leading to structural collapse of the blade during operation. The occurrence of wrinkle defects presents a great expense in the production of the blades since they are, in most cases, repaired due to lack of reliable methods of estimating the reduction in load carrying capability [3]. In order to characterise whether a given wrinkle defect is detrimental for the structural integrity of the blade, it is necessary to be able to predict the onset of delamination and its development. The cohesive zone modelling (CZM) approach provide such capabilities and was therefore chosen for the analysis of wrinkle defects.

CZM is an indirect way of applying classical fracture mechanics, where the critical energy release rate is represented by the work of tractions acting on the crack faces. The research field within the implementation of CZM into the framework of the finite element method has several contributions. The element presented here is based on the work of [4] and [5].

A user programmed element was chosen for the analysis of wrinkle defects since all options affecting results and convergence rates would be accessible to the user. This is not the case for commercially implemented cohesive finite elements. Among these options can be mentioned: order of integration, mode interaction criterion, computation of tangent stiffness matrix and internal force vector as well as non-standard result output such as element damage and average



(a) (b)

Figure 1: a) single element model undergoing rigid body translation and rotation as well as relative displacements. b) surface plot of tractions in the relative opening space.

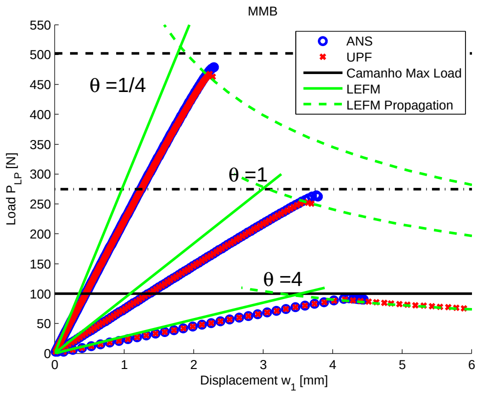
mode mixity. Furthermore, a user programmed element provides a framework in which further research can be conducted. It was chosen to implement the user programmed feature (UPF) in the ANSYS Mechanical finite element package for several reasons. ANSYS Mechanical provides a thorough documentation for implementing user programmable features along with extensive possibilities of accessing the wanted data from the element routine. ANSYS Mechanical also provides tools for plotting results of UPFs and it is possible to create and modify models through the Ansys Parametric Design Language (APDL). APDL is well suited for parametric studies, which come in handy when wrinkle defects of various sizes and compositions are to be analysed. The work carried out regarding analysis of the strength of wrinkle defects is presented in [2].

Element formulation and verification

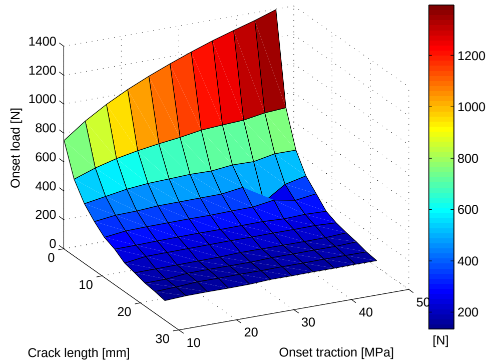
The developed UPF is a bilinear eight-noded isoparametric element with zero thickness. The element uses a bilinear traction-displacement law and is capable of simulating mixed mode crack development in 3D. The Benzeggagh-Kenane (BK) criterion [9] is used to determine equivalent properties for a given mode mixity as done in [4]. The damage evolution law is based on a single scalar damage parameter and the quadrature rule is 1. order Newton-Cotes. The computation of the tangent stiffness matrix is simplified by neglecting contributions from changing mode mixity and changing geometry from substep to substep. This simplification is made due to computational efficiency and because it is assumed that the mode mixity and geometry will change slowly. Using the UPF the global problem is turned into a nonlinear problem due to the nonlinear constitutive law and nonlinear geometric relations of the crack interfaces. Under displacement control the problem can be solved using the standard Newton-Raphson solver and under load control an equilibrium path tracing algorithm such as e.g. the Arc-Length method has to be used since snapthroughs and snapbacks may occur in simulations.

The element was verified using a two step procedure. In step one the element kinematics along with the material model was verified on a single element model shown to the right in Figure 1a. Different rigid body rotations and translations were applied to the element in order to check if convergent solutions were obtained, and thereby verify that the element kinematics was implemented correctly. For the different configurations tested, a surface plot of the traction norm in the opening space spanned by the relative displacement in the x- and y-direction of the element coordinate system was made. The surface plot of the traction norm in the relative displacement space can be seen in Figure 1b. The implementation of the material law was then validated by comparing the obtained results with a material law programmed in MATLAB.

In step two the element was validated by simulating the physical test specimens; double cantilever beam (DCB), end notch flexure (ENF) and mixed mode bending (MMB) and comparing



(a)



(b)

Figure 2: a) Load-displacement curves for MMB tests with different mode mixities. b) Surface plot of load at which unstable crack growth occurs for varying crack lengths and onset tractions.

	$\theta = 1/4$		$\theta = 1$		$\theta = 4$	
Method	Load [N]	Iterations	Load [N]	Iterations	Load [N]	Iterations
ANS	478.5	457	264.3	390	92.2	276
UPF	467.5	387	253.1	189	90.0	128
LEFM	513.5	-	277.5	-	97.3	-
Experimental	518.7	-	275.4	-	108.1	-

Table 1: Number of iterations used and load at which unstable crack propagation occurs for different mode mixities.

with the INTER205 element (ANS) in ANSYS, Linear Elastic Fracture Mechanics (LEFM) and with experiments from [6]. The FE models are meshed with 1600 elements in the length direction of the specimens in order to obtain convergent solutions for the required onset traction of 80MPa to 100MPa. The results obtained from the MMB tests are shown in Figure 2a. The mode mixity for each test is given as $\theta = \frac{G_I}{G_{II}}$. The UPF element gives the same results as the ANS on most parts of the curves and shows faster convergence (see Table 1). The reason for the difference in results between UPF and ANS is believed to be the different mode interaction criteria used. It is also seen that LEFM predicts a stiffer response and higher load for unstable crack growth. A model using CZ elements becomes more compliant than LEFM predicts because the interfaces in the cohesive zone are allowed to separate some distance defined by the constitive law before crack propagation starts.

Influence of the onset traction on the predicted load carrying capability

Using CZ elements in an FE model can potentially make the model difficult to solve due to convergence difficulties. Substantial research have been carried out in order to overcome such difficulties. Among studies on this subject can be mentioned [4], [5], [7] and [8]. Suggestions for improving the chance of convergence are e.g. modifying the tangent stiffness, lowering the penalty stiffness, increasing order of integration, lowering the onset traction and to use a very fine mesh in the damage process zone.

The DCB, ENF and MMB simulations were meshed with a mesh so fine that it would be impractical to use in the simulations of wrinkle defects. From [7] it is known that one way to use a coarser mesh without sacrifising convergence is to lower the onset tractions. This is because it enlarges the cohesive zone resulting in more elements present in this region. In order to overcome convergence difficulties when simulating wrinkle defects in [2] the onset tractions were lowered until convergence for a reasonable amount of elements was observed. In order to clarify which influence lowering the onset traction has on the predicted load carrying capability, a parametric study was conducted on the DCB specimen. The parameters varied were initial crack length and the onset traction. The results from the study are shown in the surface plot in Figure 2b. It is clear that for long cracks the choice of onset traction has an insignificant influence on the predicted load for the onset of unstable crack growth. This means that for long cracks, the energy release rate is the governing parameter. It is also observed that the predicted load for a short crack is highly dependent on the choice of onset traction. This is because the length of the cohesive zone is large compared to the crack length and the added compliance from the cohesive zone becomes significant. The study shows that if information regarding crack propagation is sought, lowering the onset traction is an acceptable way of reducing the demand for the required number of elements. However, crack initiation is highly dependent of the onset traction, since crack initiation can be seen as the limit case of decreasing the crack length. This has the implication, that the onset traction can not be lowered arbitrarily in order to obtain convergence if crack initiation is to be examined since, if the onset traction is lowered, non-physical behaviour of the model may be experienced.

References

[1] E. T. Christensen, J. Glud and J. Sjølund. *Formulation of Cohesive Finite Element for Analysing Strength of Wrinkles in Glass-Epoxy Laminates.* Master Thesis, Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark, 2013.

[2] E. T. Christensen, J. Glud, E. Lindgaard and B. L. V. Bak. *Analysing the Strength of Wrinkle Defects in Glass-Epoxy Laminates.* Proceedings of the 26th Nordic Seminar on Computational Mechanics, Eds. A. Logg, K.A. Mardal, Oslo, Norway, October 23-25, 2013.

[3] M. Leong. *The Influence of Defects on the Failure of Wind Turbine Blades.* Ph.D. Thesis, Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark, 2012, ISBN: 87-91464-44-7.

[4] A. Turon. *Simulation of Delamination in Composites under Quasi-Static and Fatigue Loading using Cohesive Zone Models.* Ph.D. thesis, Universitat De Girona, Spain, 1st edition, 2006, ISBN: 978-84-690-4372-1.

[5] V. K. Goyal. *Analytical Modeling of the Mechanics of Nucleation and Growth of Cracks.* Ph.D. thesis, Faculty of Virginia Polytechnic Institute and State University, USA, 2002.

[6] P. P. Camanho, C. G. Dávila, and M. F. D. Moura. *Numerical Simulation of Mixed-mode Progressive Delamination in Composite Materials.* Composite Materials, 37(16):1415-1438, 2003.

[7] A. Turon, C. G. Dávila, P. P. Camanho and J. Costa. *An Engineering Solution for Mesh Size Effects in the Simulation of Delamination using Cohesive Zone Models.* Engineering Fracture Mechanics, 74:1665-1682, 2007.

[8] B.L.V. Bak and E. lund. *Reducing the Integration Error of Cohesive Elements.* Proceedings of the 24th Nordic Seminar on Computational Mechanics, Eds. A. Logg, K.A. Mardal, Oslo, Norway, October 3-4, 2011.

[9] M.L. Benzeggagh and M. Kenane. *Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus.* Composites Science and Technology, 49:439-449, 1996.