11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20–25, 2014, Barcelona, Spain

AN ISOGEOMETRIC CONTINUUM SHELL FORMULATION FOR THE SIMULATION OF INTERLAMINAR FAILURE IN COMPOSITES

Saman Hosseini[1], Joris J.C. Remmers[1,⋆], Clemens V. Verhoosel[1] and René de Borst[2]

[1] Eindhoven University of Technology, Department of Mechanical Engineering, PO Box 513, 5600 MB, Eindhoven, The Netherlands. ⋆J.J.C.Remmers@tue.nl, www.tue.nl/mechmat
[2] University of Glasgow, School of Engineering, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, United Kingdom

Key words: *Isogeometric analysis, continuum shells, delamination, cohesive zone method.*

Isogeometric analysis (IGA) has recently received much attention in the computational mechanics community. The basic idea is to use splines, which are the functions commonly used in computer-aided design (CAD) to describe the geometry, as the basis function for the analysis rather than the traditional Lagrange polynomial functions. The main advantage of isogeometric analysis is that the functions used for the representation of the geometry are employed directly for the analysis, thereby by-passing the need for a sometimes elaborate meshing process. Another advantage is that spline basis-functions possess a higher order degree of continuity which enables a more accurate representation of stress states, even at inter-element boundaries. The order of continuity of these basis-functions can be reduced locally by knot insertion. This feature can be used to model interfaces and cracks as discontinuities in the displacement field [1].

In order to study failure-mechanisms in thin-walled composite materials, an accurate representation of the full three-dimensional stress field is mandatory. Therefore, a continuum shell formulation is an obvious choice. A good example is the solid-like shell element, which contains a higher-order displacement field in the through-the-thickness direction to avoid thickness locking [2]. The element allows to model a laminate by lumping all layers in a single element. A more accurate analysis is obtained when every layer is represented by a different element in thickness direction. Delamination growth can be modelled by placing cohesive zone interface elements between the solid-like shell elements.

A solid-like shell element based on the isogeometric concept has been presented by Hosseini *et al.* [3]. The work utilizes NURBS basis functions to construct the mid-surface of the shell. A complete three-dimensional representation of the shell is obtained by using a linear Lagrange shape function in the thickness direction in combination with an addi-

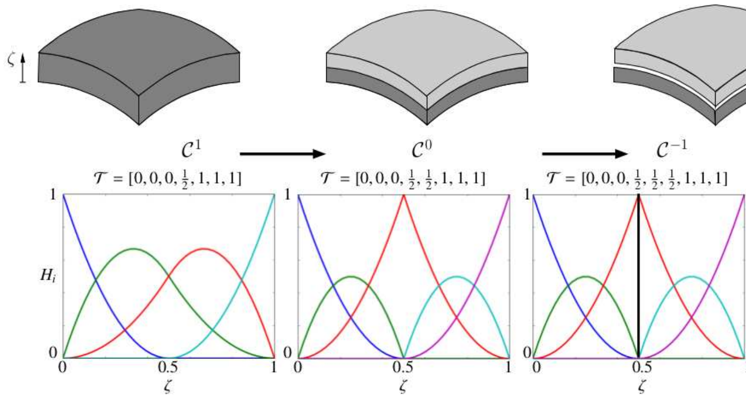

Figure 1: Schematic representation of introducing a discontinuity in the thickness direction of a shell. Weak and strong discontinuities between the layers of a composite laminate are achieved by knot insertion. In the element on the left, all layers are lumped. In element in the middle, all layers are taken into account separately. In the element on the right, a strong discontinuity is introduced to simulate a delamination.

tional stretch term. This isogeometric shell is implemented in a standard finite element code using the Bézier extraction technique. It has been demonstrated that this formulation is equivalent to the original element but requires less degrees-of-freedom to analyse curved shells. The performance of the element can be further improved when a B-spline basis function is used to discretise the shell in thickness direction [4]. This allows for the construction of a quadratic displacement field in thickness direction, without the need of an additional stretch term. Furthermore, weak and strong discontinuities can be introduced in the B-spline function using knot-insertion [1] to model material interfaces and even delaminations rigorously as discontinuities in the displacement field, see Figure 1.

In this paper, we will use the formulation with a strong discontinuity to analyse delamination growth in layered composite shells. The magnitude of the displacement jump, which represents the opening of the delamination, is controlled by a mixed-mode cohesive constitutive relation [5]. The performance of the element is demonstrated by means of a number of examples, including a delamination buckling analysis.

REFERENCES

[1] C.V. Verhoosel, M.A. Scott, R. de Borst, T.J.R. Hughes. An isogeometric approach to cohesive zone modeling. *Int. J. Numer. Meth. Eng.*, **87**(1-5), 336–360, 2011.

[2] H. Parisch. A continuum-based shell theory for non-linear applications. *Int. J. Numer. Meth. Eng.*, **38**(11), 1855–1883, 1995.

[3] S. Hosseini, J.J.C. Remmers, C.V. Verhoosel, R. de Borst. An isogeometric solid-like shell element for non-linear analysis. *Int. J. Numer. Meth. Eng.*, **95**, 238–256, 2013.

[4] S. Hosseini, J.J.C. Remmers, C.V. Verhoosel, R. de Borst. An isogeometric continuum shell element for non-linear analysis. *Comp. Meth. App. Mech. Eng.*, `http://dx.doi.org/10.1016/j.cma.2013.11.023`.

[5] A. Turon, P.P. Camanho, J. Costa, C.G. Dávila. A damage model for the simulation of delamination in advanced composites under variable-mode loading. *Mech. Mat.*, **38**(11), 1072-1089, 2006.