Isogeometric analysis of damage and fracture in thin-walled structures

René de Borst

Department of Civil and Structural Engineering, University of Sheffield
Sir Frederick Mappin Building Mappin Street, Sheffield S1 3JD, UK
e-mail: r.deborst@sheffield.ac.uk

Abstract

The basic idea of isogeometric analysis (IGA) 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 as well. A main advantage is that a sometimes elaborate meshing process is by-passed. Another benefit is that spline basis-functions possess a higher-order degree of continuity, which enables a more accurate representation of the stress. Further, the order of continuity of the 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.
In order to study failure mechanisms in thin-walled composite materials, an accurate representation of the full three-dimensional stress field is mandatory. A continuum shell formulation is an obvious choice. Continuum shell elements can be developed based on the isogeometric concept. They exploit NURBS basis functions to construct the mid-surface of the shell. In combination with a higher-order B-spline basis function in the thickness direction a complete three-dimensional representation of the shell is obtained. This isogeometric shell formulation can be implemented in a standard finite element code using Bézier extraction.
Weak and strong discontinuities can be introduced in the B-spline function using knot-insertion to model material interfaces and delaminations rigorously as discontinuities in the displacement field. The exact representation of material interfaces vastly improves the accuracy of the through-the-thickness stress field. The ability to provide a double knot insertion enables a straightforward analysis of delamination growth in layered composite shells. Illustrative examples will be given.

Keywords: isogeometric analysis, shells, plates, interfaces, discontinuities, delamination

1. Introduction

Delamination is one of the most important causes of failure in composite materials and structures. Starting with the work of Allix and Ladevèze [1] and Schellekens and de Borst [2] finite element methods have been used for the analysis of this failure mechanism. Initially, analyses were restricted to free edge delamination, and a generalised plane-strain model was used to model the propagation of delamination near the free edges. In particular, interface elements [3] were used to capture the separation process between the plies. Recently, interface elements have also been developed where NURBS have been used as the basis functions instead of Lagrange polynomials [4].

While generalised plane-strain analyses together with interface elements can give much insight in the delamination process and complement experimental investigations [2], they are less suitable for large-scale simulations. Indeed, for the analysis of structural elements in composite structures, layered shell elements have to be used. Of particular interest are the solid-like shell elements, since the presence of the stretch in the thickness direction as an independent parameter in the finite element model allows for capturing a fully three-dimensional stress state. Because the solid-like shell element developed by Parisch [5,6] only employs translational degrees of freedom, it has gained much popularity in the analysis of layered shell structures.

Composite shell structures may have a significant number of layers, and inserting interface elements between each layer where delamination could occur, quickly becomes impractical. For this reason, the extended finite element method [7,8], which exploits the partition of unity property of finite element shape functions, has been used to insert delaminations between layers [9], the main advantage being that this approach allows for the modelling of delaminations when a certain initiation criterion has been exceeded without prior knowledge about the location of the delamination being necessary. Multiple locations where delamination initiate can thus be modelled, as well as growth and joining of delaminated areas.

Recently, it has been recognised that spline functions, which are commonly used in computer-aided design (CAD), can be used as well in analysis, thus by-passing the need for meshing after the design phase [10]. Since most CAD packages are based on Non-Uniform Rational B-Splines (NURBS) these functions have also largely been adopted in isogeometric analysis (IGA).

The possibility to exactly capture the geometry can be important in the analysis of (thin) shell structures, since geometric imperfections, and therefore also imperfections in the modelling of the shell surface, can be pivotal in stability analyses of shells. Furthermore, the higher-order continuity of spline functions allows for a straightforward implementation of Kirchhoff-Love shell models [11,12], which require C^1 continuity. Although C^1 continuity is not necessary for Reissner-Mindlin shells, an IGA formulation has also been developed for this class of shell theories [13], while the 7-parameter shell model [14] was recently also cast in an isogeometric format [15].

The solid-like shell developed in [5,6] was cast in an isogeometric framework in [16]. While initially a hybrid approach was adopted, in which only the shell surface was modelled using NURBS, while a conventional Lagrange polynomial was used in the thickness direction, a full isogeometric continuum shell element was described in [17], using a B-spline function for the interpolation in the thickness direction. An important advantage of using B-spline basis functions is the ability to model weak and strong discontinuities in the displacement field by knot insertion [18], and it was demonstrated that weak discontinuities (between layers), and strong discontinuities (delamination) [19] can be modelled elegantly and accurately. For the case of weak discontinuities the superiority in terms of a vastly improved stress prediction in the linear-elastic phase was shown [17].

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