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Dune-composites – A new framework for high-performance finite element modelling of laminates

Anne Reinarz[a,*], Tim Dodwell[b], Tim Fletcher[c], Linus Seelinger[d], Richard Butler[c], Robert Scheichl[a]

[a] Department of Mathematical Sciences, University of Bath, UK
[b] College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK
[c] Department of Mechanical Engineering, University of Bath, UK
[d] Institute for Scientific Computing, University of Heidelberg, Germany

ABSTRACT

Finite element (FE) analysis has the potential to offset much of the expensive experimental testing currently required to certify aerospace laminates. However, large numbers of degrees of freedom are necessary to model entire aircraft components whilst accurately resolving micro-scale defects. The new module *dune-composites*, implemented within DUNE by the authors, provides a tool to efficiently solve large-scale problems using novel iterative solvers. The key innovation is a preconditioner that guarantees a constant number of iterations regardless of the problem size. Its robustness has been shown rigorously in Spillane et al. (2014) for isotropic problems. For anisotropic problems in composites it is verified numerically for the first time in this paper. The parallel implementation in DUNE scales almost optimally over thousands of cores. To demonstrate this, we present an original numerical study, varying the shape of a localised wrinkle and the effect this has on the strength of a curved laminate. This requires a high-fidelity mesh containing at least four layers of quadratic elements across each ply and interface layer, underlining the need for *dune-composites*, which can achieve run times of just over 2 min on 2048 cores for realistic composites problems with 173 million degrees of freedom.

1. Introduction

Traditionally, aerospace structures have been largely manufactured by subtractive processes, such as machining, which is typically applied to metals. Composite materials, which constitute over 50% of recent aircraft construction, are created at the same time as the structure itself; typically by an additive layup process such as automated fibre placement (AFP). This co-assembly of material and structure is achieved by sequential deposition of a number of fibrous layers which are either pre-impregnated or post-infused with resin, involving hundreds of additive operations during the production of a large structural part. Most of these processes take place before the resin is cured, when the influence of temperature and pressure on the deposition, forming and curing of parts with complex geometry is not well understood. For this reason production is vulnerable to defects arising from small process variations and achieving high-rate automation of the process is limited.

The ability to manufacture composite material-structural systems with repeatable properties at a reasonable rate and competitive cost, with the quality required for certification, is a major challenge in the global aerospace industry. A number of defect types can arise, and use of non-destructive evaluation is limited in detecting these, hence conservative 'knock-down' factors are applied to strength limits. These factors are currently obtained by expensive testing at all scales in the Test Pyramid, with large numbers of small coupon tests and fewer larger-scale structural tests. Large-scale tests, are extremely expensive and take place at a stage when it is difficult to make changes and improve designs, while small-scale coupons do not represent the performance of the material at the structural scale where, for example, defects can be introduced as a result of complex forming processes. Furthermore, the boundary conditions and loading in a simple element are very different from the performance of the material within the structure.

One loading of particular interest is corner unfolding, in which though thickness tensile loading acts to separate the layers as the corner radius is increased under bending loads. These stresses act in the weak resin-dominated direction of the laminate and can therefore lead to a limiting design case. The presence of defects such as mis-aligned fibres in the form of out-of-arc wrinkles can have a significant importance. Such a reduction in strength is referred to in manufacturing as a knock-down factor. A large number of composite parts contain such corner radii to provide perpendicular surfaces for attachment to other parts. The opening of these corners can be a critical limitation to the strength

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[*] Corresponding author.
E-mail address: a.k.reinarz@bath.ac.uk (A. Reinarz).

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of such radii, particularly since manufacturing defects are prone to occur in such regions of high curvature.

Mukhopadhyay et al. have modelled the effect of defects on compressive [23] and tensile [24] strength in flat laminates using 8-node, solid elements and zero-thickness, 8-node, cohesive elements between plies. Damage modelling accounted for nonlinear shear in plies, transverse matrix cracking, mixed mode delamination, tensile fibre fracture and fibre kinking. The minimum size of the FE mesh was one ply thickness (0.25 mm) in the vicinity of wrinkles and towards laminate edges. The compressive strength predictions were in agreement to within 10% of experimental results and were able to pick up a mode switch from fibre failure to delamination when defect misalignment was above ~9°. In the tensile case, it was noted that wrinkles act as local, through-thickness shear stress concentrators. For multidirectional laminates, the influence of the defect was exacerbated by edge effects.

It is well-known that the singularity associated with the free edge of laminated test specimens causes a stress concentration, especially when a laminate contains plies with fibres in varying orientations. The strength of full-sized components may therefore be misrepresented by narrow test specimens, which are frequently cut from wide laminate sections as witness specimens, to establish manufacturing knock-down factors. We have been shown previously that applying a 3 mm layer of tough resin to the curved edges of corner test specimens reduces the stress concentration and increases strength [14].

There is a wide range of defects that can form in composite laminates and a detailed taxonomy of these is presented in [25]. In this paper we evaluate wrinkle defects, which are more likely to form in curved laminates as a result of consolidation onto a male tool [10]. They are also likely to form in curved laminates with tapered sections, which causes double curvature and makes AFP deposition challenging. These wrinkles are important to the performance of curved laminates.

In this paper we present a new FE analysis tool *dune-composites* for efficient, high-fidelity modeling of laminated composite parts. We show, using a simple test case that the results of *dune-composites* match up well with the commercial software package ABAQUS in all six stresses. For large scale problems, *dune-composites* crucially relies on robust iterative solvers for the resulting FE systems. To this end, we introduce the preconditioner GenEO [27,28,20], which we have implemented within DUNE. This preconditioner has previously been mathematically proven to be robust for isotropic FE systems. + + + We show that these results extend to anisotropic problems and that the solver is suitable for solving large composites problems. Further, we demonstrate its parallel efficiency and its ability to scale to thousands of compute cores, allowing the solution of the large problems with defects mentioned above. We test this module by modeling the unfolding of a curved laminate part containing manufacturing defects, for which a micron scale mesh is needed to accurately compute stresses. We show that *dune-composites* is able to accurately predict damage initiation and that it does so at a fraction of the computational cost required by ABAQUS.

2. Modelling approach

In this section, we introduce the new high performance finite element module *dune-composites*, and demonstrate its capability of efficiently and robustly tackling large-scale simulations of composite structures. In the example simulations presented, the composite strength of pristine and defected corner radii are accurately predicted. The analysis assumes standard anisotropic 3D linear elasticity and the failure is assessed using a quadratic damage onset criterion for the initiation of delamination in [8]. This allows the results to be benchmarked against existing numerical results and experiments, given in Fletcher et al. [14]. This study shows that ultimate failure is unstable, following quickly after initiation, and so linear analysis is justified. For this case, the numerical results of this linear model show good agreement with experimental data.

The failure of curved laminates subjected to corner unfolding has been shown to be highly unstable with instantaneous propagation following initiation [14]. Therefore we focus on capturing the initiation of failure accurately by using a high-fidelity 3D mesh, with 4 or more elements through the thickness of each ply and interface layer. Such an approach has been shown to give accurate results for simple flat coupons [13] and 2D models of a few plies [16]. However, this level of fidelity is typically dropped when modelling larger, more complex parts, such as 3D curved laminates, due to computational limitations. Here, we do not use any of these more complex models in order to reduce the computational requirements.

More complex modelling approaches have been proposed for modelling of defects in the literature, these include the use of composite shell elements [24,23], interface/cohesive elements [18,21] and higher-order continuum models [22]. In particular, cohesive elements are commonly used to capture propagation [18], but propagation is considered less important than initiation for the problem. The formulation of such elements, whilst more complex, is possible within *dune-composites*. The solution strategy would require Newton iterations and path-following methods (available in the DUNE library). However, even for these non-linear models of failure, computational cost is still dominated by the speed of solving a linearised system of equations for composite materials. In this paper our focus is therefore on developing and implementing an efficient solution strategy for these linearised equations arising from such massive composite simulation.

2.1. Dune-composites: High performance FE modelling of large-scale composite structures

DUNE (Distributed and Unified Numerics Environment) is an open source modular toolbox for solving partial differential equations (PDEs) with grid-based methods, such as the finite element method (FEM) [4–6]. Written using modern C + + programming techniques, the core modules of DUNE have been developed by mathematicians and computer scientists to allow users to implement and use state-of-the-art mathematical methods across large high performance parallel computing architectures. It is a generic package that provides a user with the key ingredients for solving any FEM problem, e.g. grid generation, different types of finite elements, quadrature rules and a choice of off-the shelf solvers.

Within this platform, we have developed a new module, *dune-composites*, which solves the linear elasticity equations with general, anisotropic stiffness tensor, applicable for modelling composite structures. This module provides an interfaces to handle composite applications which includes stacking sequences, complex part geometries and complex boundary conditions such as multi-point constraints, or periodic boundary conditions. Further, we have implemented a new 20-node 3D serendipity element (with full integration) within *dune-pdelab*, which is not prone to shear locking and allows comparison with ABAQUS's C3D20R element. This element has degrees of freedom at the 8 nodes of the element as well as on each of the 12 edges.

The main advantage of implementing our simulation tool within DUNE is that it allows us to exploit developments in state of the art solvers such as Algebraic Multigrid (AMG), see [3], or to implement new ones. In particular, as part of our new developments, we implemented a novel, robust preconditioner, called GenEO [28,27], within DUNE. Finally, we will show in Section 2.4 that DUNE allows for highly parallelised efficiency on hundreds of computer cores. This allows for the modelling of meshes fine enough to resolve defects or the modelling of wide parts with sufficient accuracy.

2.2. Verification of DUNE

In this section we show that DUNE produces stress results that are comparable to those produced by standard FE libraries such as ABAQUS. For our comparison we examine a corner unfolding test in