International Journal of Solids and Structures 51 (2014) 3252–3264

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Adaptive shape functions and internal mesh adaptation for modeling progressive failure in adhesively bonded joints

Scott E. Stapleton [a,*], Evan J. Pineda [b], Thomas Gries [a], Anthony M. Waas [c]

[a] Institute for Textile Technology, RWTH Aachen University, Aachen 52074, Germany
[b] Structures and Materials Division, NASA Glenn Research Center, Cleveland, OH 44135, USA
[c] Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48105, USA

ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 26 February 2014
Available online 2 June 2014

Keywords:
Adhesion
Bonded
Crack
Finite element
Joining
Numerical methods
Adaptive shape functions
Adaptive mesh

ABSTRACT

Macroscopic finite elements are elements with an embedded analytical solution that can capture detailed local fields, enabling more efficient, mesh independent finite element analysis. The shape functions are determined based on the analytical model rather than prescribed. This method was applied to adhesively bonded joints to model joint behavior with one element through the thickness. This study demonstrates two methods of maintaining the fidelity of such elements during adhesive non-linearity and cracking without increasing the mesh needed for an accurate solution. The first method uses adaptive shape functions, where the shape functions are recalculated at each load step based on the softening of the adhesive. The second method is internal mesh adaption, where cracking of the adhesive within an element is captured by further discretizing the element internally to represent the partially cracked geometry. By keeping mesh adaptations within an element, a finer mesh can be used during the analysis without affecting the global finite element model mesh. Examples are shown which highlight when each method is most effective in reducing the number of elements needed to capture adhesive nonlinearity and cracking. These methods are validated against analogous finite element models utilizing cohesive zone elements.

1. Introduction

With the increasing demand for fiber reinforced composites in lightweight aerospace structures, adhesively bonded joints are becoming more critical than ever. Bolted and riveted joints have proven to be poorly suited for composite materials (Hart-Smith, 2002) . Unlike traditional metals, brittle fibers often do not yield significantly to spread concentrated loads introduced by mechanical fasteners. Furthermore, bolts and rivets require holes in the material to be joined, which interrupts continuous fibers and introduces additional stress concentrations. Adhesive bonding is suitable for composite materials because it is less invasive, introduces load more gradually, and can often be much more cost effective. The adhesive market has indeed grown along with the advanced composite market, and the structural adhesive market in Europe has been forecasted to reach 67,000 tons by 2015; a growth of over 13% since 2008 (Bell, 2012).

However, adhesively bonded joints are often not used in industry due to many factors. For example, it can be difficult to ensure the quality of a bonded part. A lack of redundancy in single overlap joints, which is required for many aerospace applications, can also reduce opportunities for application. Furthermore, adhesively bonded joints can be problematic to model. The models often do not scale because of fixed thickness requirements of the adhesive layers, making individual design for each joint necessary. Geometric discontinuities in adherends cause stress singularities in many models, thus non-traditional failure criteria or evaluation methods are often required. A lack of confidence in material models, failure criteria, and engineering experience results in gross over-design of joints along with safety requirements which sometimes require secondary mechanical fasteners, jokingly referred to as “chicken bolts” by many engineers.

Adhesively bonded joints are typically analyzed using analytical models (closed-form) or numerical models (finite elements). Historically, analytical models (Volkersen, 1938; Goland and Reissner, 1944; Hart-Smith, 1973a,b; Delale et al., 1981; Mortensen and Thomsen, 2002; Frostig et al., 1999; Tsai and Morton, 1994; Adams and Peppiatt, 1977; Tsai et al., 1998) were relied upon exclusively while computer capability was relatively small. Analytical models are fast, and have been used to conduct numerous parametric studies to further the understanding of the design of joints. However, assumptions are often made which allow closed-form

---

* Corresponding author. Tel.: +49 (0)241 80 24745.
E-mail address: sstaple@umich.edu (S.E. Stapleton).

http://dx.doi.org/10.1016/j.ijsolstr.2014.05.022
0020-7683/

solutions but limit joint geometry and materials which can be accurately analyzed. Furthermore, these analytical models do not couple well with larger component and vehicle models, limiting their usefulness.

Finite element (FE) models, on the other hand, are general enough to allow a wide range of geometries and configurations, and can even couple joint analysis with larger models. The improving speed of computers makes this method more viable for joint analysis. However, there are some downsides to modeling joints with FE models. The reentrant corners often cause a geometric singularity, and numerous work has been conducted to create failure theories which account for this (Crocombe, 1989; Harris and Adams, 1984; Bednarcyk et al., 2006; Zhang et al., 2005, 2006; Camanho and Tong, 2011; Towse et al., 1999). Failure methods investigated include stress-based, strain based, plastic energy density, and stress measured at a characteristic distance from the singularity. Furthermore, the extremely thin adhesive layer limits the size of elements which can be used to explicitly model the adhesive. This means that there are truly no coarse models, and coupling with vehicle-scale models can be problematic (Bednarcyk et al., 2006; Zhang et al., 2006).

One relatively new technique for modeling progressive failure of adhesively bonded joints is progressive damage modeling incorporating fracture mechanics concepts. Interface elements using different methods such as discrete cohesive zone method (DCZM) or continuous cohesive zone method (CCZM) are used to resolve the stress singularity at material interfaces and reentrant geometrical corners, and allow the faces of the adherends to separate by treating the adhesive as a network of non-linear springs obeying a traction vs. separation law (Ortiz and Pandolfi, 1999; Camanho and Dávila, 2002; Xie and Waas, 2006; Goutianos and Sørensen, 2012; Guiamatsia et al., 2009, 2010). These methods come in many different varieties, but most often involve stress-based initiation criterion and energy-based failure definitions. These methods have been shown to be extremely powerful for joints, but still have some drawbacks. Characterizing these interface elements requires a large amount of characterization tests, and appropriate handling of mode-mixicity is also a subject within the cohesive zone modeling that has yet to be satisfactorily concluded (Guiamatsia et al., 2009). Additionally, the cohesive laws utilized require an initial, numerical fictitious stiffness to prevent separation of the plies before delamination initiation. Furthermore, there is a maximum element length, based on the process zone size, required to obtain accurate results. Cohesive zone element utilizing shape functions that are enriched by an analytical solution (similar to the methodology presented in this work) have been used to alleviate mesh dependence and size requirements (Guiamatsia et al., 2009, 2010). Most cohesive elements are formulated assuming a zero-thickness interface, and thus may not be adequate to model adhesive joints, especially if the adhesive layer is thick.

Another fracture based technique for modeling crack propagation that can be applied to joint analysis is the virtual crack closure technique (VCCT) (Krueger, 2004). With VCCT fracture toughness based criteria are used to determine if it is energetically favorable for a crack to propagate. Propagation is restricted to element boundaries and typically must be known *a priori*. Thus, modeling joints with a finite thickness adhesive may prove challenging with VCCT.

All of the aforementioned methods are highly developed and have been shown to give a reasonable strength prediction for joints, but they are detailed models which require extremely fine meshes. Thin adhesive bonds, most often thinner than 1 mm, restrict the size of elements needed for the adhesive. The transition from the fine adhesive mesh to the coarser adherend mesh causes additional preprocessing work for the analyst. Therefore, joint design and analysis is typically completed after the global vehicle sizing on dense meshed sub-models, when design changes are expensive or impractical.

A need exists to develop predictive tools for bonded joints that can be seamlessly coupled with large scale structural analyses without adding major computational demands. Such tools can be used to make quick mesh-independent assessments of bonded composite joints. Furthermore, they fit in into the computational hierarchy of virtual testing of aircraft structures (Ostergaard et al., 2011), an area that is getting increased attention in the aerospace industry with the aim of lowering design cycle and certification costs.

A solution to this problem involves merging analytical models with finite elements. Simplified structural models can be used to obtain shape functions that are exact for the assumptions of the model. These shape functions can be used to formulate stiffness matrix for the problem at hand. As long as the assumptions remain valid, such an element would give the exact solution regardless of the number of elements used.

This method has been used to calculate a stiffness matrix for different beam on elastic foundation problems (Eisenberger and Yankelevsky, 1985; Aydoğan, 1995). More recently, Gustafson and Waas (2009) have created an element to capture the behavior of a double overlap joint subjected to mechanical and thermal loads.

A general bonded joint finite element has been created (Gustafson and Waas, 2009; Stapleton and Waas, 2009, 2010; Stapleton et al., 2012) wherein an entire bonded joint can be modeled with a single element. This joint element considers the adherends to behave like beams (or wide panels), and the adhesive to be made up of a bed of shear and normal nonlinear springs. The governing equations of this structural model are found and solved to produce enhanced shape functions for the joint element. Furthermore, the element has been generalized to allow multiple adherend/adhesive layers and ply drops/thickness tapers, providing the capability to model a variety of joint types with very few elements. This model was implemented in the software Joint Element Designer, which was written in C# and first conceived in a joint effort between the University of Michigan and NASA (Stapleton and Waas, 2012). However, this method loses its advantage when modeling highly nonlinear adhesives and trying to capture progressive failure. An increase in elements is required for an accurate solution, which goes against the philosophy of enhanced elements.

This paper presents two methods which allow the bonded joint finite element to capture adhesive non-linearities and cracking without increasing the mesh needed for an accurate solution. The first method is the use of adaptive shape functions, where the shape functions are recalculated at each load step based on the softening of the adhesive. The second method is internal mesh adaption, where cracking of the adhesive within an element is represented by discretizing a cracked element into multiple elements in order to accurately represent the local, cracked geometry. Both of these methods were implemented in the Joint Element Designer software. Examples are shown which highlight the savings in elements, computational time, and integration points needed when using these methods and when the methods are particularly beneficial. The performance of the various joint element methodologies are compared to analogous models using CZM elements.

Finally, these methods are shown for an adhesively bonded joint but both methods have broader application. The adaptive shape functions could be used for any element where the material and geometric properties used to obtain the shape functions are changing. Updating the shape functions within an analysis would improve the ability of the shape functions to represent the deformation of the changing material/geometry. Finally, adaptive mesh, which is not a new technique (Guiamatsia et al., 2009, 2010; Rudraraju et al., 2012a,b), can be very effective in capturing