Computational Analysis of Geometric Nonlinear Effects in Adhesively Bonded Single Lap Composite Joints

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The use of fibre composites has shown a tremendous growth in many branches during the last decades. Now the applications of composite materials span from trivial, industrial products such as boxes and covers, that are produced in enormous numbers each day, to pipelines and large, crucial, load bearing parts of constructions. Composites are also extensively used in aerospace and marine industry. Important reasons for this popularity are the high strength (and stiffness) to weight ratio and the possibility for making products of almost any geometry.

Due to the comprehensive use the need for joining composite parts to construction details made of composites or other materials is obvious. Such joints can be constructed in numbers of ways, i.e. as bolted or other mechanically fastened joints or as bonded joints. Adhesively bonded joints have the advantages over traditional mechanically fastened joints in avoiding drilled holes (broken fibres), reducing stress concentrations, etc. Joints can be symmetric (e.g. double lap joints) or non-symmetric (e.g. single lap joints).

In the following we will analyse single lap joints where two laminated plates are bonded together by a thin layer of adhesive. Similar joints have been investigated by, e.g., Hildebrand [3] and Kairouz and Matthews [4]. They study ultimate strength of single lap joints and claim that geometric nonlinear effects are important. However, they do not investigate for what values of applied loads or prescribed end displacements nonlinear effects become significant. In the present study we will focus on that aspect by comparing finite element results from geometric nonlinear models with linear simulations. We assume that the joint is wide compared to its thickness and the length of the overlap region. Furthermore, each laminated plate consists of eight plies with fibre directions 0 and 90 degrees. Thus, out of plane bending is avoided, and the joint can be investigated as a 2-D plane strain problem. The well-known software package *ANSYS* [1] is applied in the analysis. Additionally, the relatively complicated expressions defining relations between stresses and strains (including modifications related to the geometric nonlinear model from Zienkiewicz and Taylor [5]) for laminated composites are derived and implemented in a general elasticity module using the commercial C++ class library *Diffpack* [2]. This way of combining the use of a relatively robust method in *ANSYS* with a self-implemented module in *Diffpack*, in which all programming details are known, has been very fruitful and provided valuable insight into important modelling aspects (for example, it is observed that certain 2-D anisotropic problems are incorrectly treated by *ANSYS*). The agreement between the numerical results obtained by *ANSYS* and *Diffpack* is excellent for the problems in the present investigation.

The numerical, 2-D domain is shown in figure 1, which also defines the boundary conditions applied. The laminated plates consist of eight plies of thickness 0.125 mm, and the thickness of the adhesive layer is 0.1 mm. Two different stacking sequences are investigated: $[0/90]_{2s}$ and $[90/0]_{2s}$. The mesh consists mainly of four-noded bilinear elements. There are three elements through the thickness of each ply and six to eight through the adhesive layer. In addition to the bilinear elements there are some three-noded triangular elements in the spew fillet. The total number of elements is approximately 10000. The material properties, which are listed in the tables 1 and 2, are picked from Kairouz and Matthews [4], where the adherends are made of $XAS/914C$ carbon fibre/epoxy resin and the adhesive used is Ciba-Geigy Redux $308A$.

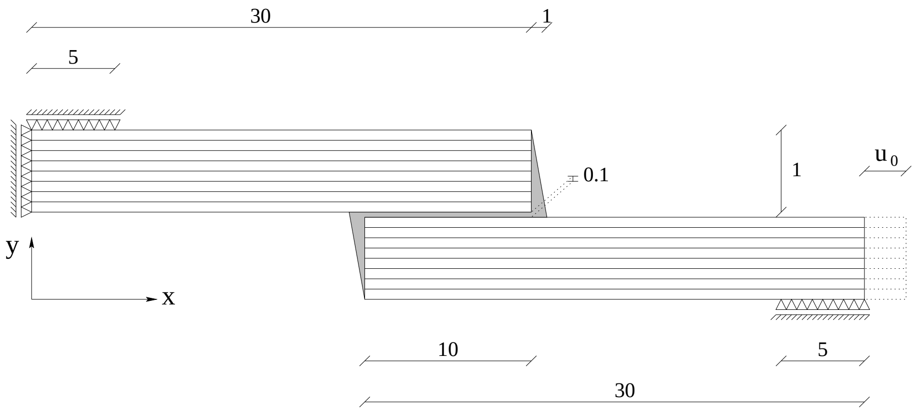

Figure 1: 2-D domain for the numerical simulations.

Firstly, we investigate the behaviour of the single lap joint with the $[0/90]_{2s}$ lay-up in the adherends. A typical distribution of the von Mises equivalent stress, resulting from the geometric nonlinear method, is depicted in figure 2 for a crucial region of the (deformed) geometry. Here, the prescribed displacement, u_0, of the right hand side boundary is 0.1 mm, which leads to stresses and strains far below critical ply crack limits. The maximum value for the equivalent stress (as well as for σ_x and σ_y) is observed near the fillet tip, while the maximum shear stress occurs in the adhesive layer near $x = 30$. Similar behaviour and values are obtained around the spew fillet at $x = 20$.

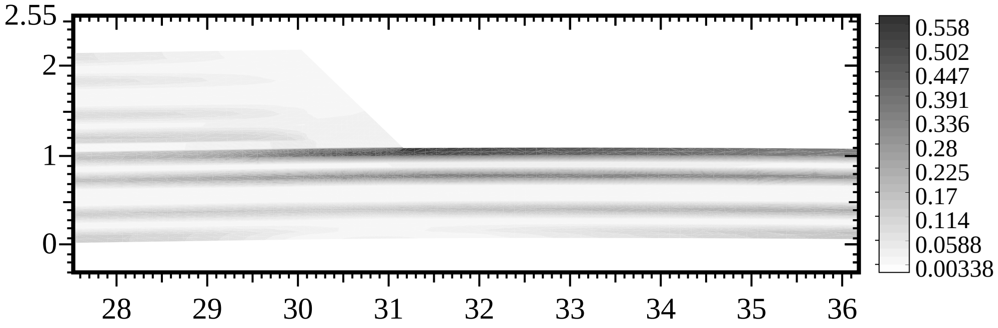

Figure 2: Distribution of von Mises equivalent stress near the fillet tip for $u_0 = 0.1$ and $[0/90]_{2s}$ stacking sequence for the adherends.

The figure 3(a) shows vertical displacement at the fillet tip as a function of u_0, while the equivalent stress is depicted as a function of the external load (per unit width) in figure 3(b). The nonlinear results are compared with solutions obtained by a linear model. Ply cracks begin to develop when $u_0 \approx 0.2$, and it is seen that nonlinear effects are significant for end displacements (or corresponding external loads) above approximately fifty percent of that value. Especially the vertical displacement shows considerable nonlinearities. However, also the equivalent stress is clearly modified

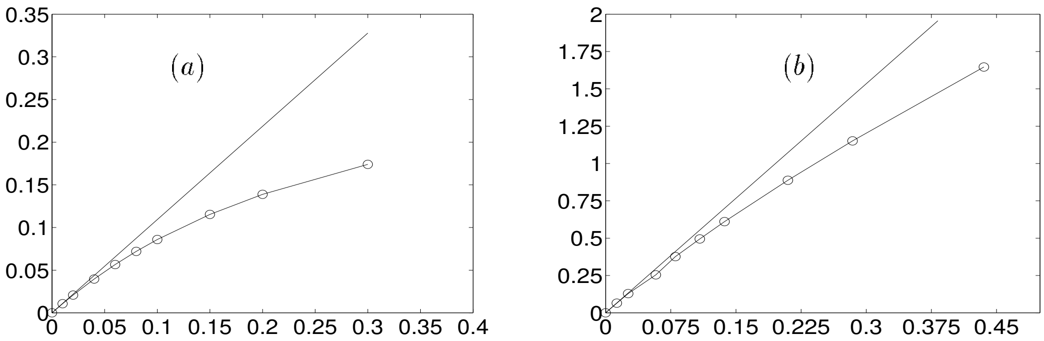

Figure 3: Comparison of geometric nonlinear ($\circ$) and linear (solid line) results. Figure (a): Vertical displacement at the fillet tip as a function of joint end displacement. Figure (b): von Mises equivalent stress at the fillet tip as a function of external load.

by nonlinear effects. A more careful investigation of each stress component proves that the normal stresses (σ_x and σ_y) are significantly modified by nonlinear effects while the shear stress behaves nearly linear. Similar behaviour is observed for the joint with the $[90/0]_{2s}$ stacking sequence.

In the present study we have seen that considerable departure from linear behaviour is observed for a large regime of prescribed displacements or external loads. Geometric nonlinear effects begin to develop for loads far below ultimate strength limits. Thus, geometric nonlinear methods should always be applied when single lap (or non-symmetric) composite joints are analysed.

Longitudinal elastic modulus, E_1 (GPa)	138
Transverse elastic modulus, E_2 (GPa)	9.4
In-plane shear modulus, G_{12} (GPa)	6.7
Major Poisson's ratio, ν_{12}	0.32

Table 1: Mechanical properties of $XAS/914C$ composite.

Elastic modulus, E (MPa)	3000
Shear modulus, G (MPa)	1145
Poisson's ratio, ν	0.31

Table 2: Mechanical properties of Redux 308A adhesive.

References

[1] *ANSYS* World Wide Web home page:
http://www.ansys.com.

[2] *Diffpack* World Wide Web home page:
http://www.nobjects.com/prodserv/diffpack.

[3] Hildebrand, M., Non-linear analysis and optimization of adhesively bonded single lap joints between fibre-reinforced plastics and metals. *Int. J. Adhesion and Adhesives*, 14 (4), 1994, pp. 261-267.

[4] Kairouz, K. C., & Matthews, F. L., Strength and failure modes of bonded single lap joints between cross-ply adherends. *Composites*, 24 (6), 1993, pp. 475-484.

[5] Zienkiewicz, O. C., & Taylor, R. L., *The Finite Element Method, Fourth Edition.* McGraw-Hill Book Company, London, 1989.