International Journal of Adhesion & Adhesives 31 (2011) 248–264

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

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

# A review of finite element analysis of adhesively bonded joints

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ARTICLE INFO

*Article history:*
Accepted 26 January 2011
Available online 24 February 2011

*Keywords:*
Adhesive bonding
Joint design
Finite element stress analysis
Fracture mechanics
Dynamic mechanical analysis

ABSTRACT

The need to design lightweight structures and the increased use of lightweight materials in industrial fields, have led to wide use of adhesive bonding. Recent work relating to finite element analysis of adhesively bonded joints is reviewed in this paper, in terms of static loading analysis, environmental behaviors, fatigue loading analysis and dynamic characteristics of the adhesively bonded joints. It is concluded that the finite element analysis of adhesively bonded joints will help future applications of adhesive bonding by allowing system parameters to be selected to give as large a process window as possible for successful joint manufacture. This will allow many different designs to be simulated in order to perform a selection of different designs before testing, which would currently take too long to perform or be prohibitively expensive in practice.



## 1. Introduction

Due to the increasing demand for energy-efficient vehicles, there is an increasing need to design lightweight structures such as aircraft and vehicle body frames. Because of this factor and due to the increased use of lightweight materials, sheet material joining techniques have been developed rapidly in recent years for joining advanced lightweight materials that are dissimilar, coated and hard to weld [1,2].

As a traditional joining method, adhesive bonding has been used for many centuries. However, it is only in the last seventy years that the science and technology of adhesive bonding has really progressed significantly [3–5]. There is considerable use of adhesive bonding in different industrial fields. Up until 2009, for example, the market demand for automobile adhesives was viewed as increasing very fast and the average per-vehicle consumption of adhesives/sealants was around 20 kg. The structural automotive adhesives would have an average annual growth rate of greater than 7% over the next five years. In the aerospace industry, more and more adhesives have been used in the construction of the aircraft culminating in the Boeing 787 and the Airbus A350 both of which contain more than 50% bonded structure [6]. This widespread use of adhesive bonding is due to ease of application, time and cost savings, high corrosion and fatigue resistance, crack retardance and good damping characteristics [7–9].

Fig. 1 shows some typical classifications of adhesively bonded joints, which are commonly found in current engineering practice. The spew can be considered as the result of the adhesive squeezed out of the lap region at the moment of the joint manufacture. The mechanical behavior of an adhesively bonded joint can be obtained by closed-form equations or experiments. For a fast and easy answer, a closed-form analysis is appropriate. In Volkersen's shear-lag analysis [10], it was assumed that the adhesive deforms only in shear, while the adherend deforms only in tension. The consequences of the rotation of the adherends were first taken into account by Goland and Reissner [11]. They derived equations to evaluate the shearing and normal stresses in the bond layer as well as those in the jointed plates, assuming that the peel and shear stresses were constants across the adhesive thickness. In Cornell's work [12], a variation and extension of Goland and Reissner's method was presented for determining the stresses in adhesive lap-joints. He assumes that the two lap-joint plates act like simple beam and the more elastic adhesive layer is an infinite number of shear and tension springs. Hart-Smith has produced an enormous amount of work on continuum mechanics of adhesive joints, for example [13–15]. His method is a development of the shear-lag analysis of Volkersen and the two theories of Goland and Reissner. The design philosophy behind Hart-Smith's work is that the adhesive should not be the weak link. Thus, if peel stresses are likely to occur, they should be alleviated by tapering the adherends (scarfing) or by locally thickening the adhesive layer.

The mechanical behavior of adhesively bonded joints is not only influenced by the geometry of the joints but also by different boundary conditions. The increasing complex joint geometry and its three-dimensional nature combine to increase the difficulty of obtaining an overall system of governing equations for predicting the mechanical properties of the adhesively bonded joints. In addition, material non-linearity due to plastic behavior is difficult

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0143-7496/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijadhadh.2011.01.006

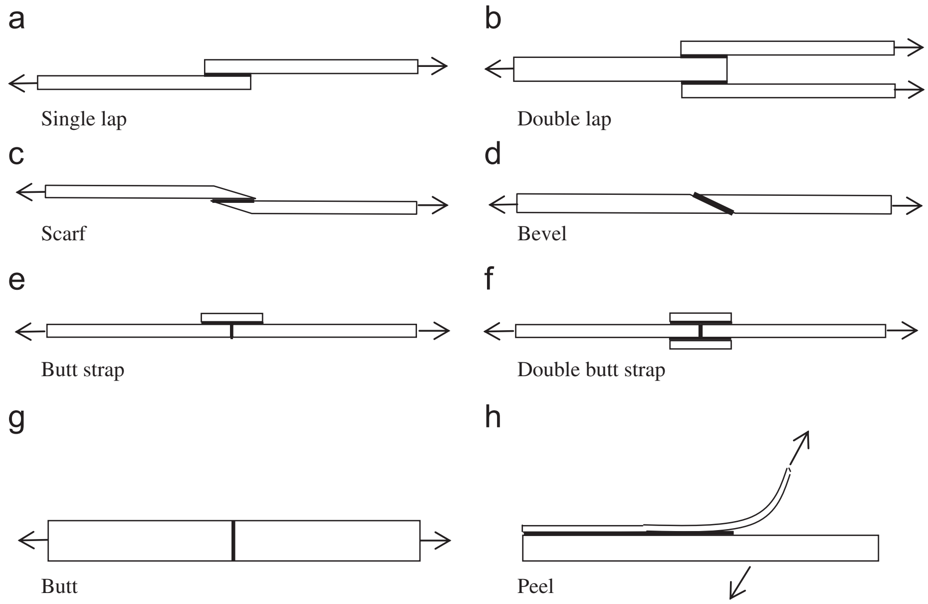


**Fig. 1.** Some common engineering adhesive joints.

to incorporate because the analysis becomes very complex in the mathematical formulation. The experiments are often time consuming and costly. To overcome these problems, the finite element analysis (FEA) is frequently used since 1970s.

The FEA has the great advantage that the mechanical properties in an adhesively bonded joint of almost any geometrical shape under various load conditions can be determined. In the case of FEA of adhesively bonded joints, however, the thickness of adhesive layer is much smaller than that of the adherends. The finite element mesh must accommodate both the small dimension of the adhesive layer and the larger dimension of the remainder of the whole model. Moreover, the failures of adhesively bonded joints usually occur inside the adhesive layer. It is essential to model the adhesive layer by a finite element mesh which is smaller than the adhesive layer thickness. The result is that the finite element mesh must be several orders of magnitude more refined in a very small region than is needed in the rest of the joint. Thus the number of degrees of freedom in an adhesively bonded joint is rather high. It is also important that a smooth transition between the adherends and adhesive be provided. Fig. 2 shows an example of smooth transition between the adherends and adhesive [16].

It is of course important to build the finite element model with a limited number of elements and nodes to save computer time. The simplified models, however, have sometimes restricted the full view and the accuracy of the results. The application of the explicit FE-codes in FEA of adhesively bonded joints has increased significantly in recent years. Using the explicit FE-codes, the equation of motion of each degree of freedom is solved individually. This allows for very large models such as detailed craft structures, which even consist of over one million degrees of freedom, to be simulated within a reasonable execution time. The limit on the degrees of freedom is due to limits in computer memory capacity and on the need to keep the solution time reasonable.

In the area of FEA of adhesive bonding, the work by Adams et al. from the University of Bristol is regarded as a seminal work [e.g., 17–27]. Adams et al. took the lead to carrying out the FEA for different adhesively bonded joints such as lap joints [17], tubular lap joints [18], butt joints [19], bevel and scarf joints [20].

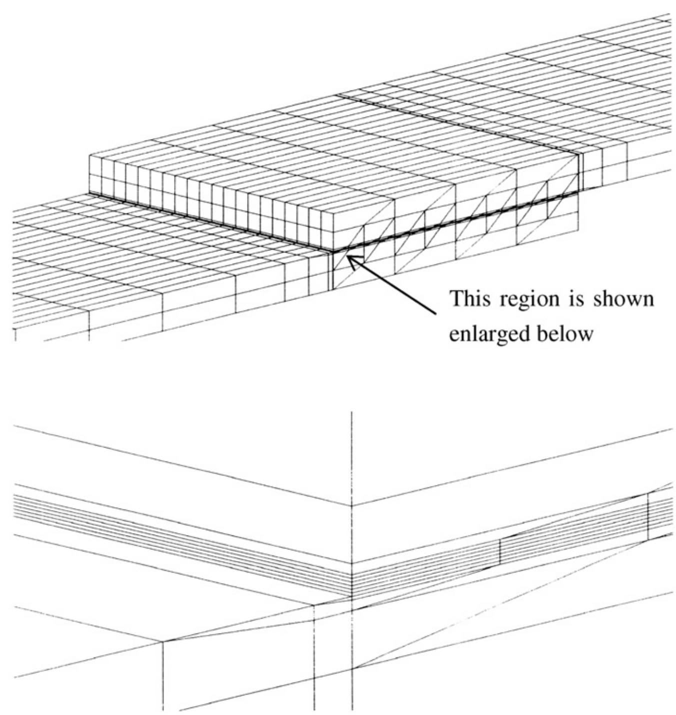


**Fig. 2.** An example of smooth transition between adherends and adhesive [16].

They also introduced elasto-plastic and non-linear FEA into adhesive bonding [21,24]. Their work has led the development of FEA in adhesive bonding.

A considerable amount of FEA has been carried out on different types of adhesively bonded joints over the years. Mackerle [28,29] gives bibliographical reviews of the finite element methods applied to the analysis and simulation of adhesive bonding. Baldan [30,31] gives very comprehensive reviews on the adhesively bonded joints in different materials. Banea and da Silva [32] give a very comprehensive review on the adhesively bonded joints in composite materials.