Composite Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Composite Structures

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

Double lap adhesive joint with reduced stress concentration: Effect of slot

Xiaonan Hou*, Armin Yousefi Kanani, Jianqiao Ye

Department of Engineering, Engineering Building, Lancaster University, Lancaster LA1 4YW, UK

ARTICLE INFO

Keywords:
Adhesive joint
Polymers
Mechanical properties
Strength
Finite element analysis (FEA)

ABSTRACT

Stress distributions at interfaces of adhesive lap joints have been widely studied to optimize overall structural strength. However, these studies focussed mainly on the mechanics of adhesive layers. In this paper, a novel concept for a double lap adhesive joint is proposed by introducing a slot in its inner adherend. Numerical simulations employing a finite-element method are used to validate the proposed concept. The results show that the introduction of the slots can smooth the stress distributions along the edges of the interfaces between adhesive and adherend and reduce stress concentration near the cut-off ends of the joint. The results also show that the height of the slots has significant effects on alternating the interfacial stresses. Thus, the proposed concept provides a promising way to optimize double lap adhesive joints for enhanced strength with reduced weight.

1. Introduction

In practical engineering applications, there are three basic methods for assembly and joining of engineering components: mechanical joints (e.g., bolted and riveted connections), physical joints (e.g., welds) and chemical joints (e.g., adhesive joints) [1]. Adhesive joints attract more attention due to their advantage of enabling the development of lightweight, cost-effective and highly integrated structures with a more uniform load distribution and improved damage tolerance [2–6]. The configurations of adhesive joints are generally classified as lap joints, butt joints, strap joints, reinforcements, cylindrical joints, T joints and corner joints [7]. Lap joints are usually used for assessing joint strength due to their relatively simple geometric features. Also, lap joints are widely used by researchers to study stress distributions in and failure mechanisms of adhesive bonding [8].

For adhesive lap joints, a uniform stress distribution in the adhesive layer would be ideal for a maximum joint efficiency. However, it is hardly achievable in practical applications due to significant stress concentrations at the ends of the overlaps. Maximum shear stress occurs at the ends of the overlaps, resulting in lower stress in the central regions. Normal (peeling) stress is also concentrated at the ends of the overlaps, usually causing failure of the joint [1,7,9–11]. In the last decade, extensive studies on stress concentrations have been performed, showing that they are determined by three main factors: a shear-lag effect, bending induced by non-axial loading and end effects caused by free surfaces at the edges of the adhesive layer [12–15]. Based on this understanding, optimization of stress distribution in adhesive lap joints became one of main focuses of research. To this end, the effects of the geometry of the two components of an adhesive lap joint, i.e., adherend and adhesive, on the interfacial stress distribution were widely studied for improving the overall strength of the joint.

Based on analytical stress models, shear-stress distribution of a thicker adhesive layer should be more uniform, leading to a higher joint strength [9,16]. However, many studies have shown the opposite [12,17–20], and that an optimum stress distribution could only be obtained for a range of low thickness of adhesive [17,18,21]. This conflict arises from the material properties of adhesive and adherend and the quality of manufacturing process [7,12]. Concerning the effect of an overlap length of an adhesive layer on the character of stress distribution, some studies demonstrated that concentrated stresses at the ends of the overlap tended to decrease with the increase in its length until reaching a certain magnitude [7,22,23]. However, with the increase of the overlap length the stress magnitude in the middle region of the overlap continuously decreases, potentially down to zero for overlaps of certain length. This means that this region does not carry any load [8,11,24–26]. Besides, many researches tried to optimize the stress distribution by introducing some specific geometric features to adhesive lap joints. For instance, a spew fillet at the ends of the overlap can effectively reduce the stress concentration, spreading load transfer over a larger area and providing a more uniform shear-stress distribution [12,27–29]. Research was also carried out to investigate the effect of a discontinuous adhesive layer on the overall joint strength [30–32], which showed that a void or a gap in the adhesive layer could affect the stress distribution in a joint, while had insignificant effect on the overall joint strength [32,33].

Compared with a large number of studies focussed on adhesive

---

* Corresponding author.
E-mail address: x.hou2@lancaster.ac.uk (X. Hou).

https://doi.org/10.1016/j.compstruct.2018.03.026
Received 12 January 2018; Received in revised form 2 March 2018; Accepted 12 March 2018

Please cite this article as: Hou, X., Composite Structures (2018), https://doi.org/10.1016/j.compstruct.2018.03.026

layers, there are only a few works dealing with analysis of the effect of geometric features of adherends on joint strength. As a basic geometric parameter, increased thickness of an adherend could reduce the level of stress concentration at the ends of the overlap, although the weight of the joint increases in this case [19,34]. Additionally, a novel lap-joint configuration, called a *wavy adherend lap joint*, was developed to optimize the stress distribution in the joint. This configuration effectively reduces stress concentrations and enhances overall joint strength [3,35,36]. However, with the use of such a configuration could increase significantly the extent of complexity of structural design. Another method is to introduce notches to the adherend, which may significantly reduce the maximum peel stress of a lap joint, as showed by numerical simulations [37,38]. This phenomenon may be due to the increased flexibility of adherend, leading to a better compliance to the deformation of the ends of overlaps. However, the method seems to influence only stresses at the ends of the adherends rather than to change the character of the stress distribution along the entire overlap. According to experimental results, this design showed only a limited influence on the overall strength.

In this paper, a novel configuration of a double lap joint is proposed by embedding a slot in its inner adherend. Using a finite-element method, a stress analysis of this design is performed. The obtained results are then compared with those for the lap joint without the slot, which shows that the introduction of the slot has favourable impact on the stress distributions along its overlaps. By changing the size of the slot, both shear and peel stress distributions along the overlaps of the joint can be tuned, and the stress concentrations at the ends of the overlaps can be reduced, potentially leading to enhanced overall strength of the joint.

2. Finite-element analysis

A configuration of a typical double-lap joint, used as a baseline design in this study, is shown in Fig. 1a. The dimensions of the outer adherend are 100 mm × 25 mm × 5 mm, representing its length, width and thickness. The dimensions of the inner adherend are 100 mm × 25 mm × 10 mm. The length of interface of the double-lap joint is 50 mm, which is also the length of the adhesive layer. The thickness of the adhesive layer is 1 mm and its width is 25 mm. On the basis of this typical joint, a novel double lap joint is developed by embedding a slot in the inner adherend as shown in Fig. 1b. The length of the slot is 45 mm; its width is 25 mm, which is equal to that of the adherends. The height of the slot is *T*; it is used as a variable defining the size of the slot. The position of the slot is fixed at this stage of research. Interface *ABCD* is between the outer adherend and the adhesive layer; *A′B′C′D′* is between the inner adherend and the adhesive layer (Fig. 1c). Analysis of stress distributions was conducted along the edges of the interfaces for the double lap joints with and without a slot.

To analyse stress distributions in the double lap joints, 3D finite-element models were developed according to the geometry shown in Fig. 1. However, it is worth noting that the FE models were only developed as a tool for evaluating the new configuration in this work. Hence, there is no specific effort in handling the effects of sharp corners in the configurations, which could induce stress singularities in the calculation. The same boundary conditions were applied to both types of double lap joints, corresponding to the fixture of a specimen in real-life lap shear tests. The surfaces of the ends (left) of outer adherends were fixed using the "ENCASTRE" option in *ABAQUS* FE software, with all the degrees of freedom of the surface constrained: U1 = U2 = U3 = UR1 = UR2 = UR3 = 0. A load of 10 kN was applied on the surface of the inner adherend in the positive *x* (U1) direction as shown in Fig. 1. To obtain comparable results, the same mesh definition was used in all models of the joints, including the type of elements (linear hexahedron element C3D8R of *ABAQUS*) and their mesh densities (Fig. 2). Elastic material properties were used for both the adherends and the adhesives. The elastic modulus of the adherends was 17,500 MPa and the Poisson's ratio was 0.4, related to a real polymer material (Grivory HTV-5H1: PA6T/6I with 50% glass fibres). The modulus of the adhesives was 5171 MPa and the Poisson's ratio was 0.3, representing a typical epoxy adhesive (3M Scotch-Weld 2214). To analyse the effect of the slot, four 3D finite-element models were developed. The models were labelled, respectively, in relation to the size of the slots and where the interfacial stresses were calculated, e.g., either Model-T-U or Model-T-L, where T is the height of the slot in the *x*-*y* plane in millimetres (Fig. 1b); U and L denotes, respectively, upper (*ABCD*) and lower (*A′B′C′D′*) interfaces. Four values of T, 0, 1, 2 and 3 mm, were considered. For instance, Model-0-U is for a traditional double lap joint without any slot, and shows stress distributions along

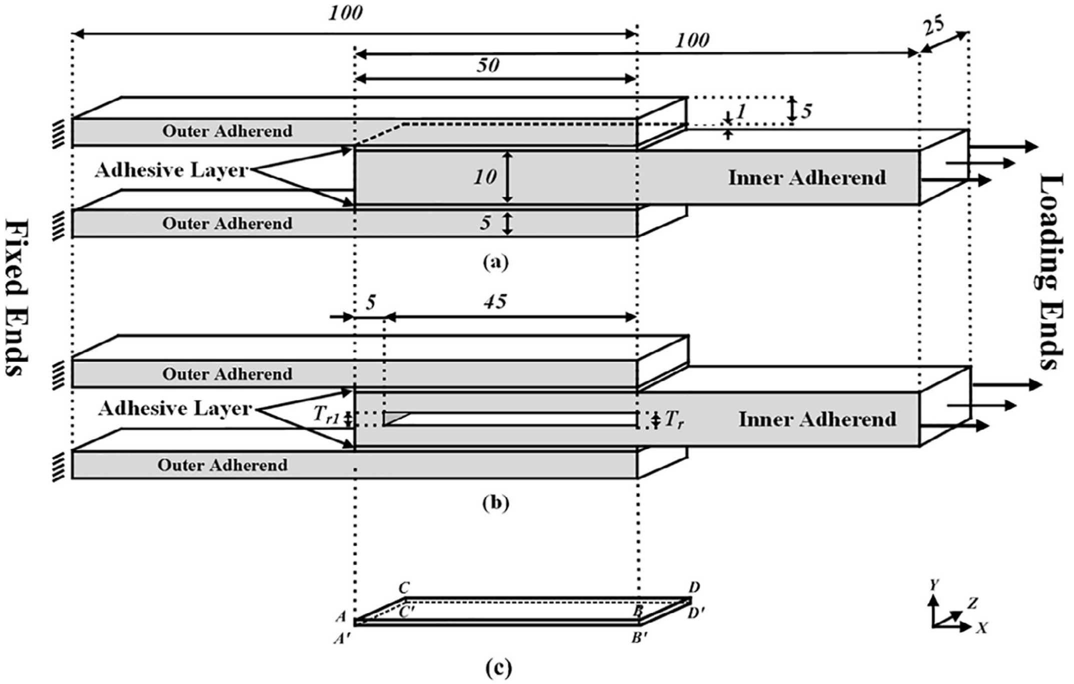

Fig. 1. Configurations of double lap joints and boundary conditions (Unit: mm): (a) without slot (typical); (b) with slot; (c) interfaces between adhesive and adherends.