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Experimental–numerical studies of transverse impact response of adhesively bonded lap joints in composite structures

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Abstract

Adhesively bonded joints in structures are subjected to in-plane and out-of-plane loads. In this work, the response of a balanced, single-lap adhesively bonded joint to a transverse normal impact load was investigated by means of LS-DYNA 3D finite element software and supporting experiments. The finite element model is based on cohesive failure in the bonded joint when the ultimate failure strain of the adhesive under transverse normal load is reached. It was found that the transverse normal load results in higher peel stress concentration in the adhesive layer as compared to in-plane loading. The increase in peel stress is due to considerable deflection of the joint under transverse normal load. Unlike in-plane loading, the stress distribution in the adhesive layer for a transverse impact load was observed to be asymmetric. The nature of the peel stress was found to vary from tensile near the edge of the lower adherend to compressive along the edge of upper adherend. The cohesive failure of the joint always initiated from the adhesive edge under tensile stress. Experiments involving low velocity impact (LVI) tests were carried out on the bonded joint to verify the results from the finite element model. The joint was prepared with carbon/epoxy adherends and three adhesives, namely, Resinfusion® 8604 epoxy, two part paste adhesive Magnabond® 6398, and 7 wt% montmorillonite nanoclay-reinforced Resinfusion® 8604 epoxy. The addition of nanoclay was found to increase the Young's modulus of the adhesive by ~20% while decreasing the ultimate failure strain by ~33%. However, no significant difference in the failure energy was observed for the joint fabricated with neat epoxy versus that fabricated with nanoclay-reinforced epoxy. Failure energy of the joint with Magnabond paste adhesive was found to be highest of the three adhesives investigated.

Keywords: Adhesively bonded joint; Transverse impact; Composite materials

1. Introduction

The quest for light and strong materials for various structural applications has led to increased use of polymer matrix composites. The need for joining these composites arises, because structures are seldom manufactured as a single unit. Adhesive joining is the most common joining technique employed for these purposes. The Boeing 747 aircraft has 62% of its surface area constructed with adhesive bonding, while the Lockheed C-5A aircraft has 3250 m^2 of bonded structure.

Features which make adhesive bonding attractive include improved appearance, good sealing, high strength-to-weight ratio, low stress concentration, low cost, corrosion resistance, and fatigue resistance. The rapid development of structural adhesives has led to the widespread use of adhesive joining technique in defense, aerospace, rail, and ground transportation applications. In these applications, the joints are designed to carry in-plane loads, although they are also prone to transverse loading from crashes, bullets, fragments, tool drops or flying debris. The usage of bonded joints in primary load

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bearing structures, especially in aerospace and military applications, makes it important to understand their failure mechanisms under transverse and in-plane loading.

2. Literature review

An adhesively bonded, single lap joint is generally characterized by a high stress concentration in the adhesive. The stress concentrated at the edges of the joint has two components, an in-plane shear stress (here after referred to as 'shear stress'), and the transverse normal stress (here after referred to as 'peel stress'), usually tensile in nature. In the case of an ideal single lap joint (rigid adherends), the shear stresses are expected to be uniform throughout the adhesive layer. In reality, the external load results in deformation of the adherends, which are constrained by the adhesive from deforming freely near the joint. This constraint causes differential deformation of the adherends, which is the primary source of shear stress concentration.

The concentration of the shear stress at the edges of the adhesive joint can result in local yielding of the adhesive. The peel stress is caused by the eccentricity in the load path, which can also cause significant bending of adherends magnifying the peel stresses. The peel stress is more detrimental to the joint performance than the shear stress [1]. Under the influence of shear stress, the adhesive yields plastically. The adherends prevent the lateral contraction of adhesive in the in-plane direction in the case of peel stresses, reducing the ability of adhesive to deform plastically and leading to brittle failure.

Various attempts have been made to model the behavior of single lap, bonded adhesive joints [1–10]. The deformation of the adhesive in bonded joints is usually treated as a plane-strain, plane-stress condition. The deflection in the joint region is caused by eccentricity in the load path, which is usually simulated by introduction of a joint edge moment, M_0, and joint edge shear force, V_0, along with the applied in-plane load per unit width T. The approximation requires the force system to satisfy the condition given by Eq. (1) to be in equilibrium. Most of the models have used this assumption to predict the stress distribution in the adhesive layer of a bonded joint.

$$V_{\mathrm{o}} = \left[\frac{T}{2}(t+\eta) - M_{\mathrm{o}}\right] \Big/ c, \tag{1}$$

where $2c$ is the joint overlap length and t and η are the adherend and adhesive thicknesses, respectively.

The initial closed form solutions for adhesively bonded joints were based upon the shear lag model [2]. The shear lag model treats the adherends as one-dimensional bars and takes into account the shear deformation in the adhesive layer only. Goland and Reissner [3] modified this model by consideration of the adherends as beams bonded to the shear- and transverse normal-deformable adhesive layer. The beam-on-elastic-foundation model allowed calculation of both shear and peel stress distributions in the adhesive. However, the model assumed a thin layer of adhesive, and neglected the adhesive material properties in the calculation of edge moments. It ignored the shear deformation and transverse normal deflection in adherends for the purpose of stress calculation.

Hart-Smith [4–6] improved upon the Goland and Reissner model for treatment of joints containing elastic–plastic adhesives. He showed that the actual stress–strain behavior of the adhesive could be approximated as linear elastic–linear plastic as long as the total area under the curve remains the same. This model considered the deformation of the upper and lower adherends separately. It also took into account the adhesive properties in the edge-moment calculation. However, the model neglected the large deflection in the overlap, and considered deflection only in the outer adherend. This limited the model to the case of short overlap and thin flexible adhesives. Oplinger [7] overcame this limitation by the inclusion of large deflections in the overlap region and the effect of bond layer thickness on stress distribution in the adhesive.

Failure of an adhesively bonded joint depends upon the crack initiation site and the path of its propagation and can be classified as (a) adhesive failure between adhesive and adherend where the crack initiates and propagates along the interface, (b) cohesive failure within the adhesive, when the crack initiation and propagation is contained within the adhesive layer, and (c) crack initiation at joint edge due to peel stresses and its propagation in the adherend causing failure of adherend, often interlaminar in nature. Chai [8] investigated the effect of thickness of the adhesive on the fracture behavior in adhesive joints under Mode I loading. This study concluded that fracture energy becomes stabilized at a bond thickness less than 0.03 mm, or greater than 0.5 mm, while the maximum fracture energy was observed at 0.22 mm.

The study of impact response of adhesive joints has received limited attention compared to quasi-static loading. In general, the strength of a rigid adhesive is not a strong function of loading rate unless the process of rearrangement of polymer chains is affected. Modifiers, such as elastomeric particulates, generally increase the toughness of the adhesive and tend to increase the impact energy due to the viscoelastic response of the adhesive.

Bezemer et al. [9] reported higher energy absorption when an adhesive was subjected to dynamic as opposed to quasi-static loading. They reported increased energy absorption even in a brittle epoxy adhesive when