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Numerical design and multi-objective optimisation of novel adhesively bonded joints employing interlocking surface morphology

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ABSTRACT

A novel concept for joining materials is presented which employs adhesive joints with interlocking bond-surface morphology formed on the surfaces of male and female adherends that mechanically interlock in shear when brought together. In the present work, miniature, single-lap joint specimens with a single truncated square pyramid interlocking profile, centred in the bond area, are investigated. The performance of the concept is assessed through finite element analysis (FEA) by incorporating yield criteria representing plasticity in the adherends and a cohesive zone model to represent damage in the adhesive layer. This allows for effective simulation of the joint response until ultimate failure and thus, full assessment of the concept's performance. Various interlocking geometries are explored and refined through an adaptive surrogate modelling design optimisation procedure coupled with FEA. The results indicated that significant improvements in work to failure, of up to 86.5%, can be achieved through the more progressive failure behaviour observed compared to that of a traditional adhesively bonded joint. Improvements in the joint's ultimate failure load can also be achieved with a relatively ductile adhesive system.

1. Introduction

Joining is a critical element of engineering design. It provides the ability to achieve structural size and shape complexity which is beyond the capabilities of primary manufacturing processes; allows for optimal material selection and usage; provides impact and damage tolerance beyond that inherent in the materials of construction; and facilitates disassembly for repair or responsible disposal of components. Each of these features directly influence the cost of a structure, which is a key driver in any engineering design. However, joining also represents one of the greatest challenges in the design of structures in general, as the strength of a joint dictates the strength and efficiency of the surrounding structure.

There are three fundamental processes by which materials and structures can be joined: (1) mechanical fastening, (2) chemical bonding, and (3) thermal joining. In consideration of structural applications, bolting, adhesion and welding are the primary techniques of choice. Individually, these technologies present inherent weaknesses which are outlined through the abundance of publications on each. Bolted joints are reliable but result in inefficient connections which reduce the strength of parent materials by introducing a stress concentration; and also add weight to the structure. Adhesive bonding provides greater efficiency but its uptake in load-bearing structures has been slow, due primarily to unpredictable joint strengths caused by variability in surface preparation techniques, which can lead to certification issues [1]. Safety considerations often require that adhesively bonded structures, particularly those employed in primary load-bearing applications, include mechanical fasteners as an additional precaution [2,3]. These practices result in heavier and more costly components. Welded joints present difficulty when joining dissimilar materials and often have lower structural stiffness than equivalent adhesively bonded joints.

The aforementioned techniques have undergone significant development in the past number of decades in order to approach the pinnacle of their potential performance. More recently, a number of hybrid methods, which combine the positive traits of the fundamental processes, have been developed in literature. Mechanical/thermal-adhesive joining techniques, such as bonded/bolted and weld/bonded joints, have been considered in relation to improving damage tolerance of adhesive joints [4–10]. The Welding Institute has also developed an entirely novel technique for joining composites to metals [11]. Given the significant developments in materials science and manufacturing technology, there is a momentous opportunity for the development of new hybrid joining processes which may leverage the evolution of joining technology in the 21st century.

The present work focusses on the development of a novel, hybrid

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mechanical-adhesive joining technology. The central bond region of a traditional adhesively bonded joint is widely recognised as being relatively inactive for load transfer and during joint failure. Rather, load is predominantly transferred through the overlap ends and failure is typically a direct function of the stress state in these regions, where the highest strains occur and normal and tangential stresses localise in the adhesive layer. As a result, fracture typically initiates in the adhesive at the free ends of the joint overlap, leading to sudden and catastrophic failure. Some authors have even shown that removing the adhesive in the central overlap region of the joint causes minimal effect to the adhesive stress state, i.e. recessed adhesive joints [12]. Previous authors have shown that modifications of the bond surface topology can alter the stress state in the adhesive bond line, culminating in compelling improvements in both ultimate failure load and damage tolerance of adhesive joints [13,14]. In order to activate the central bond region of the joint, the concept under consideration employs interlocking profiles, formed on the surfaces of male and female adherends, coupled with a layer of adhesive. The interlocking surfaces could serve to increase mechanical loading within the joint akin to mechanically fastening and thus improve reliability. They should also distribute load more evenly across the lap area and delay crack propagation through the adhesive; thereby overcoming some of the major weaknesses of traditional adhesive joints.

Herein, the joining concept is investigated through finite element (FE) analysis for a miniature adhesive joint with a single, interlocking profile in the centre of its bond area. A cohesive zone damage model (CZDM) is used to simulate damage in the adhesive and capture the response of the joint until catastrophic failure. Various profile geometries have been investigated in order to develop a fundamental understanding of the underlying mechanics of the interlocking joint and assess the performance of the concept. In order to efficiently explore the design space and determine the most effective interlocking geometry, an adaptive surrogate modelling design optimisation (ASMDO) methodology is employed. A multi-objective evolutionary optimisation algorithm is subsequently applied directly to the surrogate model to fully outline the performance envelope of the concept through a Pareto optimal design front.

2. Methodology

2.1. Joint geometry

The test specimen geometry was chosen, conductive to associated experimental work, as an adhesively bonded miniature single-lap joint (SLJ), shown in Fig. 1a. This specimen was similarly adopted by O'Dwyer et al. [15] and allows for in situ testing within an SEM chamber. In order to simplify the FE mesh, no adhesive fillet was included in the model geometry. A single truncated square pyramid surface profile, centred in the 35 mm^2 bond area, was investigated. This morphology represented the most fundamental interlocking design, allowing for its influence on joint performance to be effectively investigated. The surface profile was parametrised into four factors; length (X_1), depth (X_2), width (X_3), and inclination angle (X_4) (Fig. 1b), so that its design may be subsequently optimised. Thus, the interlocking joint consisted of a female adherend, with a depression in its surface and a male adherend, with a protruding profile defined to fit the female adherend. The adherends were coupled with a constant thickness adhesive layer, of 55 μm [15], between the interlocking surfaces (see Fig. 1a).

Table 1
Mechanical properties of the aluminium alloy, AA5754 [17,18].

E	ν	σ_y	K	n	σ_{uts}
68 GPa	0.33	111.46 MPa	496.4 MPa	0.31	299.58 MPa

2.2. Finite element model

Implicit simulations were conducted with Abaqus® [16]. The test specimen was loaded in quasi-static, displacement controlled tension from the grip locations shown in Fig. 1a. The adherends were simulated as an aluminium alloy, AA5754 [17]. The stress-strain response of the alloy was sourced from literature [18], salient mechanical properties are summarised in Table 1. The response of the alloy was characterised by elastic-plastic behaviour incorporating von Mises yield criteria. Post-yield response was represented by isotropic strain hardening defined through Holloman's equation [19] (Eq. (1)). This material was represented by 8-node, linear, brick elements with reduced integration and hourglass control (C3D8R) [16]. No damage model was implemented in the adherends as cohesive failure of the joint was assumed.

$$\sigma = K\varepsilon_p^n \tag{1}$$

where σ is the true stress, K is the strength coefficient, ε_p is the true plastic strain and n is the strain hardening exponent.

The adhesive adopted in this investigation was a bi-component structural epoxy resin, Loctite® Hysol 9466 [20]; its bulk mechanical properties were characterised comprehensively by Goglio et al. [21] and are summarised in Table 2. A cohesive zone damage model (CZDM) was implemented in consideration of damage within the adhesive layer. The CZDM chosen is implemented in Abaqus® 6.14 [16]. It is a coupled mixed-mode CZDM and thus accounts for interaction between both normal (mode I) and tangential (mode II & III) deformation of the adhesive layer. In the FE mesh, the adhesive layer was represented with its true thickness by a single layer of 8-node cohesive elements (COH3D8). In each mode the response of these elements obeyed a bi-linear traction-separation law with linear softening. This response has been shown to approximate the true mechanical behaviour of a constrained adhesive layer in pure mode I [22] and pure mode II [23], as demonstrated by Högberg [24].

The initial stiffness of the cohesive elements is governed by a penalty parameter, k, determined according to the Abaqus® user's manual [16]. Interaction between each mode of loading for the initiation of damage was accounted for according to the quadratic stress criterion, as per Eq. (2). This rule has previously achieved excellent agreement to

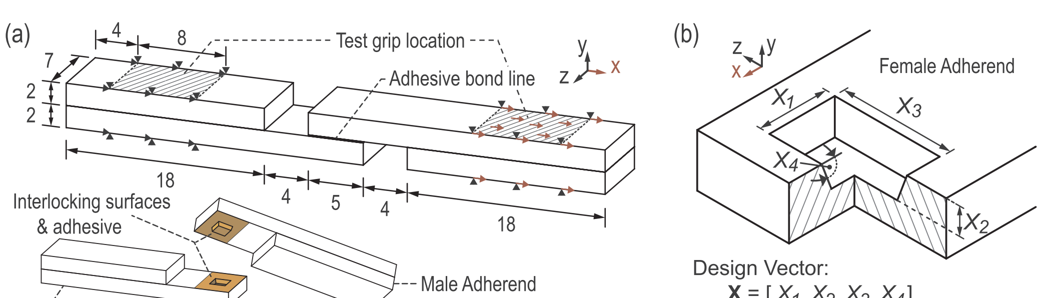

Fig. 1. Miniature SLJ (a) geometry and boundary conditions, with dimensions in millimetres and (b) truncated, square pyramid interlocking profile geometry and corresponding geometric factors.