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An experimental and analytical study of the mechanical behaviour of adhesively bonded joints for variable extension rates and temperatures

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Abstract

In the present paper, mechanical behaviours of adhesively bonded joints are studied with the help of double lap shear (DLS) coupon tests conducted at different extension rates and temperatures. The joint specimens are made from dual-phase steel coupons bonded with epoxy resin. Tests are also carried out to ascertain the behaviours of these component materials. It has been found that at a high temperature, the adhesive joint exhibits a greater degree of strain rate sensitivity with a perceptible fall in the joint strength. However, at a low temperature, the joint strength remains comparable to that at room temperature. A new semi-analytical solution procedure is developed considering material nonlinearity to predict mechanical behaviours of adhesively bonded DLS joints. The joint behaviours using the semi-analytical approach are predicted separately using the Von Mises (VM) and Raghava yield criteria. It has been found here that the application of the Raghava criterion yields good correlation with test load–extension behaviours for most temperatures and extension rates considered; on the other hand, the VM condition gives rise to perceptibly softer joint behaviour when compared to test data at a high temperature.

Keywords: Epoxy/epoxides; Steels; Lap shear; Analytical prediction

1. Introduction

The automotive industry envisions that an optimized vehicle, in terms of performance and cost, can be achieved by using different materials at different vehicle locations to utilize the materials' functionalities to the fullest extent. In this context, structural adhesive bonding creates an opportunity for additional versatility in modern car body design and manufacturing. However, there are a number of obstacles to the widespread exploitation of adhesive technology for automotive applications. One of the issues is the performance of adhesively bonded joints under impact conditions and at extreme surrounding temperatures. The information available in the published literature primarily pertains to the behaviours of metallic joints with polymeric adhesives at room temperature and under quasi-static loading conditions. For example, under the latter conditions, experimental, analytical and numerical studies have been reported [1–4]. Using a slightly modified version of the ISO11003-2 tensile-shear test procedure, results of both experimental and finite element-based studies of a bonded metal joint were reported in [1]. Tests of double lap shear (DLS) specimens were carried out under ambient conditions at a displacement rate of 25.4 mm/min [2,3]. De Moura et al. [5] studied mechanical behaviour of composite bonded joints containing strip defects. They tested carbon-epoxy single lap joints under quasi-static conditions, and performed numerical simulations using interface finite elements and mixed mode damage model based on indirect use of fracture mechanics. They concluded that the presence of a defect slightly affects the specific strength of the joint; however, the specific strength was not affected by the size of the joint. Tsai and Morton [6] tested single lap

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joints of aluminium with strain gauges and moiré interferometry to investigate nonlinear deformations and adhesive stress distributions. Dean et al. [7] tested adhesively bonded scarf, T-peel and single lap joints at quasi-static conditions. They studied limitations in the suitability of elastic–plastic models for describing the deformation behaviour of a rubber-toughened adhesive. Relatively few studies are reported under strain rates higher than quasi-static conditions: for example, the works of Zgoul and Crocombe [8], Beevers and Ellis [9], Kihara et al. [10] and Srivastava [11]. Zgoul and Crocombe [8] tested single lap joints at three different strain rates. They studied modelling of rate-dependent response of adhesively bonded single lap joints and found that the rate-dependent Von Mises (VM) material model gave closer predictions than the overstress-based visco-plastic model. However, the same authors also found yield criteria with hydrostatic effect like Raghava/exponent Drucker–Prager (EDP) to yield close prediction ofadhesive shear stress–strain behaviour (unlike VM condition-based prediction), but faced difficulties in convergence using ABAQUS in simulation of joint testing. Beevers and Ellis [9] developed a drop weight impact rig for high strain rate testing of bonded joints. They tested single lap joints of mild steel at quasi-static and at high strain rates, and obtained higher ultimate strengths at high strain rates. Kihara et al. [10] developed experimental equipment to measure the shear strength of adhesive layers subjected to impact loads. Srivastava [11] tested the effects of glueline thickness, glueline length, etching time, temperature, exposure time and strain rate on C/C–SiC composite and Ti–6Al–4V alloy adherences before and after adhesive bonding. He showed that the adhesive bond strength increases with the increase of strain rate and decreases with increase in exposure temperature.

Adams et al. [12] studied the performance of single lap joints at low and room temperatures. They investigated the effects of adherend mismatch, shrinkage and adhesive properties on the stress state of lap joints. Kang et al. [13] compared bond strengths of three types of film adhesives using double lap joints tested at room temperature and cryogenic environment. They concluded that the selection of adhesive for extreme temperatures requires adhesive testing at operating temperature range in advance. Owens and Lee-Sullivan [14] tested single lap joints at room temperature and at $-40\,^{\circ}$C at quasi-static conditions. They studied stiffness loss due to crack growth in composite-to-aluminium joints. The effects of post cure duration and temperature on cohesive performance of an epoxy adhesive have been studied experimentally by Stewart et al. [15] and the information generated can be useful in maximizing the strength of adhesively bonded joints. An experimental investigation on variable modulus adhesives for optimized joint performance has been reported by Fitton and Broughton [16]. They outlined a practical method for fabricating joints with a variable modulus bondline and similar composite adherends, and further confirmed earlier theoretical predictions on joint behaviour with simultaneous use of low and high stiffness adhesives at appropriate regions in a joint. The performance of adhesive joints at high and low temperatures using similar and dissimilar adherends and dual adhesives has been studied by Da Silva and Adams [17]. The latter study advances the understanding of the behaviour of dual adhesives in joints at different ambient temperatures, and addresses an important design need for joining adherends with different material properties such as titanium and a fibre-reinforced composite.

Recent developments in dual-phase (DP) steel offer an attractive option to the automotive designer for weight reduction and improved safety performance. For example, the use of DP steels, as opposed to more conventional steel products such as high-strength low alloys (HSLA), in some cases may result in up to 40% part weight reduction at similar vehicle crash performance [18]. DP steels, which rely on a microstructure of ferrite and martensite, have a high initial work hardening rate leading to better distribution of plastic strain and improvement of uniform elongation. This work hardening rate produces a much higher ultimate tensile strength than that of conventional-high strength steels with similar initial yield strengths. DP steels also exhibit greater total elongation when compared with conventional high-strength steels. These characteristics provide improvements in both formability and structural performance in automotive components. Studies have been done on the strength of lap joints at various temperatures and strain rates separately; but the studies did not consider the mechanical behaviour at various strain rates and temperatures in combination. Moreover, there is no performance data available in the literature of adhesively bonded DP steel joints.

A number of theoretical models have been proposed for stress analysis of adhesively bonded joints. Volkersen [19] proposed a simple shear lag model for single lap joints based on the assumption of one-dimensional bar-like adherends with only shear deformation in the adhesive layer. Goland–Reissner solutions [20] are one-dimensional elasticity solutions for shear and peel stress distributions in the adhesive layer. Hart-Smith [21] extended the Goland–Reissner model to treat joints with elastic–plastic adhesives. Suhir [22] provided a theoretical analysis of cylindrical DLS joints. Delale et al. [23] developed two-dimensional closed-form solutions for bonded joints. Oplinger [24] applied a layered beam approach to investigate the effect of adherend deflection on adhesive stress distributions. Tsai et al. [25] improved classical solutions of double lap and single lap joints by accounting for adherend shear deformations. An analytical study of cylindrical adhesive joining in the elastic range has been presented more recently by Nemes et al. [26].

The equations obtained from stress analyses do not give a direct relation between joint load and deflection which are directly measurable in a physical test with reliability. Owens and Lee-Sullivan [27] developed a stiffness model for single lap joints by summing over a series of tension and