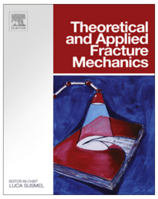
Theoretical and Applied Fracture Mechanics 80 (2015) 79–86

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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



Effect of adherends and environment on static and transverse impact response of adhesive lap joints

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ARTICLE INFO

Article history:
Available online 13 August 2015

Keywords:
Adhesive joint
Impact strength
Mechanical characterization

ABSTRACT

Impact response of adhesive joints has received limited attention compared to quasi-static loading. On the other hand, there are very few studies combining moisture and its effect on the impact strength. Therefore, the present paper aims to study the effect of moisture on the tensile and impact strength of single lap joints with different adherends (high limit elastic steel and a commercial composite). It was possible to conclude that adhesive joints with steel adherends are very sensitive to the environment and exposure time. For adhesive joints with composite adherends, the water showed a marginal effect. A marked hygrothermal effect was observed for all joints. For impact loads the environment effect is similar, but much more severe than that observed in tensile tests. For both tests, adhesive failures occurred for adhesive joints with steel adherends and delaminations for joints involving composite.

1. Introduction

Adhesive joints are designed essentially to carry in-plane loads, however, they are also subjected to transverse loadings like crashes and tool drops. In this context, it is very important to understand their failure mechanisms under transverse and in-plane loading. On the other hand, the impact response of adhesive joints has received limited attention compared to quasi-static loading.

According to Beevers and Ellis [1], for adhesively bonded steel adherends, the ultimate strength under impact is higher than under quasi-static loading, which is attributed to the deformation and strain rate sensitivity of the steel adherends. Kihara et al. [2] concluded that, for low incident stresses, the failure is promoted by the tensile stresses, while, for high incident stresses, the fracture is mainly promoted by shear stresses with a small contribution of the tensile stress. Reis et al. [3] studied the influence of superposition length on transverse impact response of single-strap adhesive joints. For this purpose low-velocity impact tests were performed using a drop weight-testing machine with a hemispherical impactor falling at the centre of a bi-clamped specimen. They were considered three gap lengths with: $\ell_0 = 0$, 10 and 20 mm, and they concluded that joints with higher ℓ_0 have higher impact energies, despite the lower bonding area, as consequence of the lower local deformation. According with the numerical analysis, the zero gap ($\ell_0 = 0$) gives maximum peel stress and increasing the gap distance decreases the stress level. In the same study, authors observed that the behaviour in three point bending tests was very similar with that observed for the impact tests. The maximum average load occurred for specimens with gap length of $\ell_0 = 20$ mm, while the gap length of $\ell_0 = 0$ mm gave the lowest maximum average load. These tests promote a bunch of superposed loads and load directions inside the adhesive layer, because considerable deflection of the adherend occurs. Therefore, adhesive joints are sensitive to changes on the superposition length under transverse and in-plane loading [3–7]. For Vaidya et al. [8], transverse loading promotes considerable deflection of the adherend, which leads to a higher peel stress concentration as compared to the in-plane loading. The magnitude of the maximum peel stress was found to be higher than for in-plane loading of the joint and the failure in the case of transverse loading initiates under mixed mode conditions compared to its in-plane loading, where it is shear dominated. The crack always initiates from the edge of the lower adherend where the peel stress is tensile in nature [4,8].

According to Sawa et al. [9], it is known that the maximum stress occurs at the edges of the interfaces in single-lap adhesive joints subjected to static tensile loadings. However, the maximum stress occurs close to the edges (not at the edges) of the interfaces in the joints subjected to impact loadings as consequence of the stress wave reflections and interferences [10]. For example,

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http://dx.doi.org/10.1016/j.tafmec.2015.07.004
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Higuchi et al. [11] found that the maximum principal stress has its maximum near to the edge of the upper interface between the adhesive and the upper adherend (the upper surface of which is subjected to impact loadings). On the other hand, the maximum stress occurs close to the edges (not at the edges) of the upper interface in the joints subjected to three-point impact bending moments, as consequence of the stress wave reflection and interference. In this context, the effects of Young's modulus of the adherends, the lap length, the adherend thickness and the adhesive thickness on the stress wave propagation at the interfaces were also studied by Higuchi et al. [11]. They found that the maximum stress increases as Young's modulus of adherends, the lap length and the adhered thickness increase. On the other hand, the maximum stress increases with decreasing adhesive thickness.

About the durability of adhesive joints in the presence of water, several studies can be found [12–19], but in terms of its effect on the impact strength, there are very few works according to the authors' knowledge. In fact, the majority of factors influencing moisture absorption and the mechanical properties of polymers are understood relatively well [14]. Water sorption into adhesive joints, with non-absorbing adherends, can be made through the bulk adhesive and/or in the interfacial region between adhesive/adherends. Once within the adhesive joint, water influences the adhesive by plasticisation, swelling or it interrupts the interfacial bonds and promotes non-reversible damages [12,14].

Therefore, the main goal of the present work is to study the effect of moisture on the tensile and impact strength of single lap joints with different adherends. For this purpose, distilled water (at room temperature and at 40 °C) and sea water will be used, and their effect will be analysed for different exposure time. The results obtained from the tensile tests and impact tests will be confronted.

2. Material and experimental procedure

Docol 1000 high elastic limit steel plates, with 1.5 mm thickness, and composite plates, with 2 mm thickness, were the material used for the adherends of the single lap joints studied. The main mechanical properties of the Docol 1000 are presented in Table 1 and were obtained from the datasheet of the supplier. The chemical composition (% weight) is: C = 0.15, Si = 0.50, Mn = 1.50, P = 0.01, S = 0.002, Nb = 0.015, Al = 0.04 and Fe = Rest. The mechanical performance of the Docol 1000 high elastic limit steel results from annealing at 750 °C following hardening by quenching in water. The steel acquires its final structure by tempering, where it is heated between 200 and 400 °C. Both the annealing and tempering are carried out in a controlled atmosphere to prevent the steel from oxidising. The final microstructure contains the martensitic phase which improves the strength of steel. More details about Docol 1000 high elastic limit steel can be found at [20]. On the other hand, Pecolit is the commercial name of the composite plates used and they are made by unsaturated polyester resin-reinforced with glass fibres. The total fibre fraction is 24.8% and they are present in two-directional balanced form. The main mechanical properties are presented in Table 1 according with the datasheet of the supplier. More details about Pecolit can be found at [20]. These materials were selected, because they are used in the automobile industry, particularly in the construction of buses.

Table 1
Mechanical properties of the adhesive and adherends.

Material	σ_{UTS} (MPa)	σ_{YS} (MPa) strain 0.2%	E (GPa)
Adhesive (Araldite® 420 A/B)	35	27	1.85
Docol 1000 high strength steel	1000	700	208
Pecolit	90	–	8.2

The specimens were manufactured as 10 mm wide bars cut from the plates, and bonded with "Araldite® 420 A/B" adhesive (properties are presented in Table 1 [21]). According with the supplier is a two-component room temperature curing, epoxy adhesive of high strength and toughness. The geometry and dimensions of the specimens are shown in Fig. 1 and combinations of steel/steel, steel/composite and composite/composite were studied. Careful surface preparation was developed in order to obtain improved adhesion. Abrasive polishing with silicon carbide paper type P220 was used and, finally, the surface was cleaned with dry air and alcohol. Finally the specimens were immersed into distilled water at room temperature, into distilled water at 40 °C and into sea water at room temperature. The exposure time studied was 1, 2, 4 and 8 weeks.

Static tests were carried out using a Shimadzu AG-10 5 kN universal testing machine, equipped with a 5 kN load cell and TRAPEZIUM X software, at a displacement rate of 5 mm/min. Five specimens were tested for each configuration until the final failure of the joint. Charpy impact tests were performed according to ISO 1792. The tests were carried out in a Ceast 9050 impact tester with 60 mm span and an instrumented impact hammer of 5 J (Fig. 2). The impact system is equipped with a D.A.S. 8000 junior (strain gauge type) high speed data acquisition and impact processing system characterised by one acquisition channel for strain gauge strikers, 14 bit resolution, 2 Mhz sampling rate a/d converter 8000 data points collected and stored. Five specimens were tested for each configuration.

3. Results and discussion

3.1. Static strength

Tensile tests were carried out to obtain the tensile strength of single lap joints with dissimilar adherends (steel/steel, steel/composite and composite/composite). Fig. 3 shows the typical load–displacement curves obtained. The curves have a nearly linear behaviour and they are according with the studies developed by Reis et al. [7] with similar adherends. The strain at failure and the maximum load show the same tendency, for each type of configuration, but with different values. The highest values are obtained for single lap joints with steel and, in the opposite tendency, the lowest values are obtained with composites. Table 2 shows the average values obtained and respective standard deviation.

It is possible to observe that the adhesive joints with steel/steel adherends present the highest loads, and they are around 257.5%

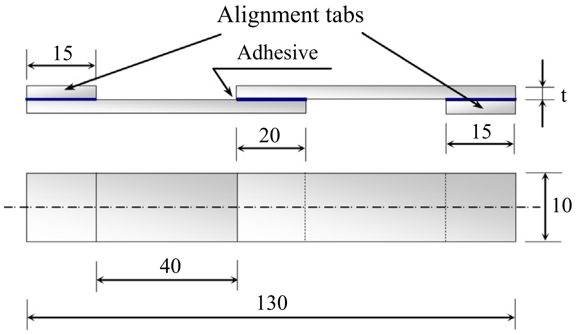

Fig. 1. Specimen geometry with 80 μm adhesive thickness and t = 1.5 mm for Docol 1000 and t = 2 mm for Pecolit (dimensions in mm).