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Effect of material, geometry, surface treatment and environment on the shear strength of single lap joints

Lucas. F.M. da Silva [a,*], R.J.C. Carbas [a], G.W. Critchlow [b], M.A.V. Figueiredo [a], K. Brown [c]

[a] Departamento de Engenharia Mecânica e Gestão Industrial, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] Institute of Surface Science & Technology, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK
[c] Chemetall PLC, Denbigh Road, Bletchley, Milton Keynes MK1 1PB, UK

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ABSTRACT

The single lap joint is the most studied type of adhesive joint in the literature. However, the joint strength prediction of such joints is still a controversial issue as it involves a lot of factors that are difficult to quantify such as the overlap length, the yielding of the adherend, the plasticity of the adhesive and the bondline thickness. The most complicated case is that where the adhesive is brittle and the overlap long. In any case, there is still a problem that is even more difficult to take into account which is the durability. There is a lack of experimental data and design criteria when the joint is subjected to high, low or variable temperature and/or humidity. The objective of this work is to carry out and quantify the various variables affecting the strength of single lap joints in long term, especially the effect of the surface preparation. The Taguchi method is used to decrease the number of experimental tests. The effect of material, geometry, surface treatment and environment is studied and it is shown that the main effect is that of the overlap length.

In order to quantify the influence of the adhesive (toughness and thickness), the adherend (yield strength and thickness), the overlap, the test speed, the surface preparation and durability on the lap shear strength, the experimental design technique of Taguchi was used in the present study. An experimental matrix of 18 tests was designed and each test was repeated three times. The influence of the eight previously-mentioned variables could be assessed using the statistical software Statview®. In this paper a simple predictive equation is proposed for the design of single lap joints.

1. Introduction

The single lap joint (SLJ) is very common in practice and simple design rules should be available for design purposes. Hart-Smith [1] proposed a chart where the joint strength is given as a function of adhesive ductility and overlap. The adherend is supposed to remain in the elastic range. This is not realistic since the substrates will yield in many cases (e.g. aluminium or low strength steel). The ASTM 1002 standard proposes a very simple design rule to guarantee that the adherends do not yield. Adams et al. [2] developed a simple methodology to predict the joint strength. If the adhesive is very ductile, typically with more than 20% shear strain to failure and the adherends are elastic, the joint strength is given by the load corresponding to the total plastic deformation. If the adherends yield, the joint strength is governed by the adherends yielding independently of the type of adhesive. For the case of a rather brittle adhesive and elastic adherends, the methodology does not work and Adams et al. [2] proposed the finite element method. The above simple design rules are very useful and can give a good prediction for many cases. There are, however, a number of parameters that are not considered in previous studies such as the adhesive thickness, the type of surface treatment and the durability.

The adhesive thickness has an important effect on the joint strength. Experience shows that the lap joint strength increases as the bondline gets thinner [3,4]. Several arguments have been proposed in the literature to explain the influence of the bondline thickness. Adams and Peppiatt [3] attribute the joint strength decrease with adhesive thickness to the fact that thicker bondlines contain more defects such as voids and microcracks. Crocombe [5] explains that as the adhesive gets thicker, the plastic spreading of the adhesive along the overlap occurs more rapidly. Interface stresses were shown to be higher for thicker bondlines by Gleich et al. [6] and da Silva et al. [4]. More recently, Grant et al. [7] explained the influence of the adhesive thickness with the bending moment. For a lap joint under tension, the longitudinal stress from the direct load and the bending moment at the edge of the overlap region create plastic strains when the steel becomes

* Corresponding author. Tel.: +351225081706; fax: +351225081445.
E-mail address: lucas@fe.up.pt (L.F.M. da Silva).

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Table 1
Adhesive shear properties using the thick adherend shear test method ISO 11003–2 (three specimens tested for each adhesive).

	Araldite® AV138 M/HV998	Araldite® 2015	Sikaflex-255 FC
Shear modulus G (MPa)	1559 ± 11	487 ± 77	1.351 ± 0.04
Shear yield strength τ_{ya} (MPa)	25.0 ± 0.55	17.9 ± 1.8	8.26 ± 0.30
Shear strength τ_r (MPa)	30.2 ± 0.40	17.9 ± 1.8	8.26 ± 0.30
Shear failure strain γ_f (%)	5.50 ± 0.44	43.9 ± 3.4	330 ± 27

Table 2
Adhesive critical strain energy release rate in mode I (G_{Ic}) measured with the double cantilever beam ASTM D3433–99 (three specimens tested for each adhesive).

	Araldite® AV138 M/HV998	Araldite® 2015	Sikaflex-255 FC
Critical strain energy release rate in mode I G_{Ic} (N/m)	345.9 ± 47.8	525.7 ± 80.8	2901.1 ± 121.9

plastic and these cause failure in the adhesive. The lap joint under tension is very sensitive to adhesive thickness. There is a longitudinal stress from the direct load together with an additional bending stress due to the load offset which is superimposed on the tension stress. To reach the same stress level, as the bending moment increases, the smaller the stress due to direct load has to be. As the bondline thickness increases, there is an increase in the bending stress since the bending moment has increased. Consequently the strength of the joint is reduced.

The adherend thickness is also important for two reasons [8]. For low strength adherends, an increase in thickness is beneficial because the adherend becomes stronger and less likely to deform plastically. On the other hand, for high strength adherends, a higher thickness can decrease the joint strength due to an increase of the bending moment.

The presence, or otherwise, of a surface treatment is another parameter that can significantly affect the joint strength. Most results in the literature are for mechanical treatments such as shot-blasting [8–10]. In the case of steel, which is the type of substrate studied here, chemical conversion coatings offer several advantages such as high treatment rates, good uniformity and, particularly, the increased durability in adverse environments where the treatment confers a degree of corrosion protection preventing joint failure through the resultant friable hydrated metal oxide [9,10].

The objective of the present study was to quantify the influence of the adhesive, the adherend, the adherend and adhesive thicknesses, the overlap, the surface treatment and the durability on the lap shear strength by using the Taguchi method [11] and to propose a simple predictive equation that work for any type of situation. A similar study was carried out by the authors in [12] and it was found that the surface treatment had little effect. However, the effect of the durability was not investigated. The main purpose of the present study is to extend the previous study and assess if the previous results are valid when durability is involved. The test speed was also investigated to assess any viscoleastic behaviour.

2. Experimental programme

2.1. Materials

Three adhesives were selected: a very ductile polyurethane adhesive (Sikaflex-255 FC); a very brittle two-component epoxy adhesive (Araldite® AV138/HV998 from Huntsman) and an intermediate two-component epoxy adhesive (Araldite® 2015 from Huntsman). The adhesives were tested in pure shear according to the thick adherend shear test (ISO 11003-2). The specimens were tested in an MTS servo-hydraulic machine 312.31 at a crosshead speed of 0.5 mm/min. Three specimens were tested for each adhesive. The shear mechanical properties of the adhesives used are shown in Table 1. The yield strength was calculated for a plastic deformation of 0.2% in the case of AV138/HV998. For the more ductile adhesives the yield strength was considered to be equal to the shear strength. To quantify the type of adhesive, the toughness was used by measuring the critical strain energy release rate in mode I (G_{Ic}) with the double cantilever beam specimen (ASTM D3433-99). The specimens were tensile tested in an MTS servo-hydraulic machine 312.31 at a crosshead speed of 1 mm/min. Three specimens were tested for each adhesive. The results are presented in Table 2.

The adherends selected were a low strength steel (DIN St33) with $\sigma_{ys} = 184$ MPa and a high strength steel (DIN C65 heat treated) with $\sigma_{ys} = 1260$ MPa.

2.2. Joint geometry

The SLJs had an overlap of 12.5, 25 or 50 mm and a width of 25 mm; see geometry in Fig. 1. The adherend thickness was 1, 2 or 3 mm. The SLJs were manufactured individually in a mould and the adhesive thickness was controlled by packing shims. Three values of adhesive thickness were used: 0.5, 1 and 2 mm.

2.3. Surface treatment

2.3.1. Mechanical treatment (P)

The bonding area was initially degreased with acetone, abraded with a ♯180 SiC sandpaper and again cleaned with acetone before the application of the adhesive.

2.3.2. Chemical conversion coating (A1)

In all cases, process chemicals used (Gardoclean S5174, Gardobond 901, Gardolene D6800, Gardolene V6513 and Gardobond R2604) were from Chemetall Ltd. (Milton Keynes, UK). Mild steel coupons were first spray cleaned with degreaser Gardoclean S5174, a proprietary process, at a concentration of 30 g/l at 50 °C for 2 min. This was followed by a cold water rinse. Coupons were then sprayed at 70 °C, for 30 s with Gardobond 901 to produce an amorphous phosphate coating. A nominal coating weight of approximately 0.4 g/m^2 was produced. A further cold water rinse was carried out. A second treatment with Gardolene D6800 was then carried out. This is a liquid, acidic, chromium-free, reactive final seal for phosphate-based conversion coatings, applied by immersion. Gardolene D6800 was applied from solution at a