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An investigation on the strength of single lap adhesive joints with a wide range of materials and dimensions using a critical distance approach

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ABSTRACT

Several criteria have been proposed for failure load prediction of adhesively bonded single lap joints (SLJs). However, the presence of factors such as the bimaterial interface, the ductility or brittleness of adhesives and also the singularity at the bonding ends make the failure prediction of SLJs a challenging issue. Recently a distance based failure load prediction method named CLS (critical longitudinal strain) was applied successfully on SLJs with different bonding lengths. This method uses a specific distance and the critical longitudinal strain as failure parameters. In this paper, the CLS was used on a variety of SLJs with a wide range of materials and geometries. Five types of adhesives including epoxies, silicones, bismaleimides, polyurethanes and acrylic were considered and the substrates consisted of different steels and aluminum alloys. The results show that the CLS can predict the failure load of SLJs with different adhesives including ductile and also brittle adhesives very well. Also, there is a good correlation between the predictions and the experimental data for SLJs with different dimensions. It was also found that the critical longitudinal strain is a function of the substrate thickness and also the Young's moduli of the substrate and adhesive. A relation was proposed for the prediction of the critical longitudinal strain in SLJs with different configurations.

1. Introduction

The advantages of adhesive joints in relation to traditional fasteners such as welding and riveting make it an important alternative bonding method in several industries. However, the complexity of the geometry and some factors such as the bimaterial interface phenomena make it difficult to reach a comprehensive model for the failure load prediction of this type of bonding. Good survey of methods suitable for adhesive contact modelling was provided by Sauer [1]. Several failure load prediction criteria have been proposed by researchers corresponding to different joint geometries and materials. The combination of analytical models such as those of Volkersen [2] and Goland and Reissner [3] with maximum stress or strain criteria can be considered as the first failure load prediction approaches [4,5]. Rahman et al. [6] also studied the peel stress as a failure parameter for joints with brittle and ductile adhesives with both adhesive and cohesive failure. The authors then proposed the crack tip opening angle (CTOA) technique for failure prediction of adhesive joints with ductile adhesives when the adhesive thickness varies. The shear stress was also considered in some other works for tubular [7,8] and double lap [9] adhesive joints. However, da Silva et al. [5] showed that the shear based criterion have limitations when applied on SLJs. The authors showed that this approach was applicable only for joints with ductile adhesives and short overlaps. For short overlap SLJs, Karachalios et al. [10] and Crocombe [11] recommended global yielding of the adhesive as a failure estimation criterion. In some other studies, shear strain instead of stress was considered for failure load assessment in adhesive joints [10,12,13]. The main shortcoming of the stress or strain based approaches in numerical analyses is the mesh sensitivity. Element size especially at singular points can influence the failure load predictions considerably. Also, it was found that using stress or strain criteria with analytical models cannot predict failure load precisely. Moreover, depending on the failure parameter, the stress or strain based criteria are usually limited to joint with ductile or brittle adhesives. However, Weißgraeber and Becker [14] combined the stress parameter with the Finite Fracture Mechanics approach and showed that their model is not sensitive to mesh size. The generalized stress intensity factor (GSIF) [15–17] and the J-integral [18,19] which are based on the linear elastic fracture mechanic (LEFM) principles was considered later in some studies. However, the LEFM method is applicable on joints with brittle

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adhesives and the mesh sensitivity is one of the main shortcomings of the GSIF approach. To overcome this problem, Fraisse [18] used Goland and Reissner [3] stress distribution to apply the J integral as a failure criterion. It should be noted that the analytical models such as that of Goland and Reissner [3] cannot present a precise stress distribution along the adhesive layer specially around singular points. This method is also only applicable to joints with brittle adhesives. To overcome the stress singularity at the bonding ends and also the mesh sensitivity problem, some researchers proposed distance based models [9,20,21]. According to these criteria, the failure parameter should be measured at a specific distance away from the singular point. Suzuki [20] worked on scarf joints. He showed that failure in a scarf joints occur if the axial stress at a critical distance away from the bonding edge reaches a specific value. John et al. [9] showed that the shear stress at a specific distance away from the bonding ends in a double lap joint can be considered as the failure parameter. Martiny et al. [21] analyzed the cracked double cantilever beam (DCB) and the tapered double cantilever beam (TDCB). They introduced a criterion based on the maximum principal stress at a critical distance. A distance based criterion named CLS (critical longitudinal strain) was also recently proposed for the failure load prediction of SLJs [22]. According to this approach, the longitudinal strain along the adhesive mid-plane was introduced as the failure parameter. The method was applied successfully on SLJs with different bonding lengths [22].

In the present paper, the CLS method was further developed on SLJs with a wide range of material properties and dimensions. Based on two experimental failure loads taken from the literature, the critical distance and critical strain for each condition were obtained with a finite element analysis and the CLS approach. By knowing the CLS constants, the failure loads of the studied joints were predicted. Then, the joints were categorized based on the adhesive mechanical properties. Further analyses performed and a relation between the critical longitudinal strain and the joint properties was proposed.

2. Joint geometry

To study the CLS failure load prediction of SLJs with a variety of dimensions and also to investigate the effect of geometry on the CLS critical values, SLJs with different configurations were considered. The dimensional features of SLJs that were considered in the present work are shown in Fig. 1. In this section, the dimensions of the studied SLJs and their effect on the strength of SLJs are reviewed. Table 1 gives all dimensions of the studied SLJs taken from the literature.

2.1. Overlap length (L)

The overlap length is the main influencing geometrical feature on the strength of SLJs [23]. The effect of overlap length differs whether the adhesive is ductile or brittle [24]. In this study, joints with short and long bonding length with ductile and brittle adhesives were studied. The joints studied by Goglio et al. [25] were considered for the shortest overlaps. They tested SLJs with a bonding length of 5 mm and a bondline thickness of 0.1 mm. The longest overlap length found was 108 mm in [22]. The authors used an epoxy based adhesive with a bondline thickness of 0.35 mm for bonding aluminum alloys.

2.2. Substrate thickness (T)

Some researchers [12,23,26,27] have discussed the effect of substrate thickness on the joint strength. According to these studies, increasing the adherend thickness caused a higher joint stiffness and subsequently decreases the joint out of plane deformation which results in a more evenly stress and strain distributions along the adhesive layer. Also, the failure load increases in SLJs with thicker adherends due to a reduced peel strain and stress effects [27].

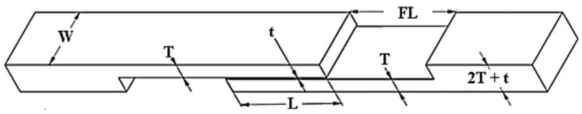

Fig. 1. - Dimensional features of the studied SLJs.

Table 1
Dimensions of the studied SLJs (mm).

Joint series	L	t	T	FL	W	Ref.
A	35, 50, 71, 108	0.35	3	22	12.55	[22]
B	10, 12.5, 20, 25, 30, 40	0.22	3, 5, 10	3, 64	25	[12]
C	12.5, 25, 50	0.12	1.5	65.5	25	[28]
D	12.5, 25, 50	0.5	3	70	25	[51]
E	12.5, 25, 50	1	2	70	25	[24]
F	25, 50	0.2	2	70	25	[52]
G	12.5, 20, 25, 40, 60	0.1	1.6	63.5	25	[10]
H	12.5, 25, 37.5, 50	0.2	3	65, 71, 78, 84	25	[37]
I	12.5, 25, 50	0.5	2	70	25	[53]
J	10, 15, 20, 25, 30, 35, 40, 50	0.15	7	10	25	[54]
K	5, 15, 25	0.1	4	32	20	[25]
L	12.5, 20, 25, 40, 60	0.1	1.6	63.5	25	[50]

In the present work, the CLS method was applied on joints with several substrate thicknesses. One of the thinnest adherend used was that by da Silva et al. [28]. In their work, high strength steel with 1.5 mm thickness was bonded using an epoxy adhesive. The thickest adherend was used by Morais et al. [12]. The authors used a steel alloy with a thickness of 10 mm for manufacturing the adhesive joints.

2.3. Adhesive thickness (t)

The bondline thickness is one of the most challenging issues in the strength prediction of SLJs. Researchers [29–33] have studied the effect of bondline thickness on the strength of SLJs. According to their results, the strength of SLJs decreases for thicker bondlines. However, in contrast to joints with brittle adhesives, the decrease trend for ductile adhesives is less pronounced [33]. In this paper, joints with a bondline thicknesses of 0.1 mm and a very brittle adhesive [10] and thick layers of 1 mm with a very ductile adhesive [24] were analyzed using the CLS method.

2.4. Free length (FL)

There are a few studies about the effect of the free length on the strength of SLJs [34–36]. A smaller free length leads to lower peel and shear stresses along the adhesive layer and consequently the failure strength increases which is in accordance with experimental results [34]. The smallest free length found in the literature is 3 mm for the thick adherend lap shear test performed by Morais et al. [12] and the longest is 84 mm for the joints studied by Nunes et al. [37].

2.5. Joint width (W)

According to the experimental results obtained by Gultekin et al. [38], the failure load of SLJs almost increase proportionally with the joint width. The global yielding criterion [11] also predicts a linear increase in the strength with the joint width. In the present work, the width of the analyzed SLJs is mainly 25 mm. However, in some studies (for instance, Ayatollahi et al.[22]), joints with a smaller width were investigated.