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Strength prediction and reliability of brittle epoxy adhesively bonded dissimilar joint

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ABSTRACT

This paper deals with strength and failure prediction as well as reliability issues of adhesive joints of brittle epoxy bonding of two dissimilar adherends. Effects of bond thickness and scarf angle upon the strength of such joints are also addressed. Three kinds of adhesive joints, i.e., butt, scarf and shear joints, are considered. It is found that the strength prediction of various adhesive joints under consideration can be done by establishing interface corner toughness, H_c, parameter. For adhesive joints with an interfacial crack, fracture toughness, J_c, or interfacial toughness, K_c, can be used as a fracture criterion depending on the fracture type observed. The predicted strengths based on these fracture criteria (i.e., H_c, J_c and K_c) are in good agreement with experimental data obtained. Weibull modulus is a suitable parameter to define the strength reliability of adhesive joints. From experimental data, scarf joint of 45° is identified to be preferable since it satisfies both outstanding load-bearing performance and tolerable reliability. In addition, the Weibull statistical method has made possible the strength reliability determination of non-cracked adhesive joints.

1. Introduction

Integrity and reliability of adhesive joints are very crucial in structural engineering and industrial applications. Therefore, destructive testing and stress analyses are essential in predicting the performance of adhesive joints. In general, strength and failure predictions of adhesive joints are either based on strength of materials or the fracture mechanics approach [1]. Nevertheless, these predictions remain tolerably difficult due to lack of sufficient criteria with sound physical basis [2,3]. In the case of adhesive joints bonded with relatively rigid brittle adhesive resin, so far, there is some evidence that presents the relation between strength and bond thickness of such joints can be satisfactorily estimated by means of stress singularity based fracture parameters, i.e., interface corner toughness, H_c, or critical fracture energy, G_c.

Some investigators validated experimentally the H_c stress intensity factor parameter. For instance, Reedy and Guess [4] accurately predicted the dependence of cylindrical butt joint's strength upon the bond thickness by using H_c approach. They also reported the difference of measured strength between joints with steel-steel and aluminium–aluminium adherends. This "adherend's stiffness effect" has been correlated to the difference in order of stress singularity at the interface corner. Further, Reedy [5] examined the connexion between interface corner and interface fracture mechanics approaches using both asymptotic and finite element solutions. The applicability of both techniques to the problem of unstable failure which initiates from an interface corner has been validated.

In another study, Akisanya and Meng [6] used their experimental results to support the application of H_c as a fracture initiation criterion at the interface corner of bonded joints. Using elastic-plastic finite element analysis, they concluded that in order for H_c to be applicable, failure process zone (i.e. or plastic zone) should be fully embedded within the region over which the singularity dominates the stress field. Qian and Akisanya [7] reported the tensile strength prediction of scarf joints subjected to a combination of mechanical and thermal loading by H_c fracture criterion with a good accuracy. This study led to a better understanding of failure mechanisms and influences of joint geometry and cure temperature.

Most recently, Mintzas and Nowell have applied H_c fracture criterion for predicting the strength of adhesively bonded butt, scarf and double lap joints [8]. To predict the strength of these joints, they employed asymptotic stress analysis combined with a path independent contour integral method. They reported that the predicted joint strengths are comparable to those experimental results found in the literatures. The conditions under which this H_c fracture criterion is valid are also discussed.

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With the progress of fracture mechanics methodology, many researchers have analysed the strain energy release rate (SERR) or stress intensity factor (SIF) to predict the strength and growth of a cracked adhesive joint. This approach is actually a complementary approach to that of stress magnitude and distribution analysis. However, the stress intensity factor of adhesive joint is not easily determinable when the crack grows at or near to an interface because it exhibits oscillatory singularity behaviour so it has indefinite value. Thus, many studies dealing with adhesive joints tends to use SERR instead of SIF [9]. It was reported that the G_c (i.e., critical SERR) can be employed as a mixed mode fracture criterion [10]. There are many techniques available that can be used to determine the SERR in finite element (FE) analysis, e.g. J integral, virtual crack closure, virtual crack extension and stiffness derivative. Rice's J integral, which is the most popular, has been widely used to predict the strength of adhesive joints having a crack with fairly good results [9,11].

Reliability analysis is crucially required in engineering safety design, especially in the strength prediction of brittle materials; ceramic components, rock, timber, etc. Based on recent interest in this similar study, Weibull statistics based probability approach receives increasing attention and appears to be the most widely used in practice. More recently, Weibull strength distribution approach has been proven by some researchers to be the most promising failure criterion and also as an effective reliability indicator for joints bonded with brittle adhesive [12–14]. Even so, rather less work has been undertaken to facilitate the design of adhesive joints. Some investigations are briefly reviewed below.

Seo and Lim [12] have investigated experimentally the values of tensile, four-point bending and shear strength using thermosetting epoxy resin based adhesively bonded butt joints. They reported in their study, the effects of adhesive sectional area (i.e., 2×3, 3×4, 4×5 and 5×6 mm^2) and compared the above mentioned test methods in terms of joint strength, standard deviation and Weibull modulus, m. It was observed that strength for tensile and four-point bending specimens decreases with increasing adhesive sectional area. They concluded that specimen with adhesive sectional area of 5×6 mm^2 has the highest strength probability in the tensile and shear tests, while in the four-point bending test is 3×4 mm^2. Besides, shear specimen is least affected by the adhesive sectional area if compared to other test methods and yet has similar strength probability to those in the tensile specimens.

Arenas et al. [13] proposed the use of a statistical analysis based on Weibull distribution to define an optimum bond thickness that combines the best mechanical performance (i.e., shear tensile strength) with high reliability. In their experimental study, they applied acrylic adhesive to manufacture the single lap joint with 6160 aluminium alloy adherend. As a result, the optimum bond thickness for their single lap joint was reported as 0.5 mm.

Vallée et al. [14] have developed a probabilistic method based on Weibull statistical distribution for the strength prediction of balanced adhesively bonded double lap joints composed of pultruded GFRP adherends. They also presented a short review regarding the size effects on strength of materials and FRP composites.

Hadj-Ahmed et al. [3] proposed a strength probability law to predict the shear strength of a double lap adhesive joint through analytical and numerical investigations. They related the influence of both bond thickness and overlap length upon joint strength to the Weibull modulus, m. The adhesive behaviour varies in accordance to the m value (i.e., $m\leq3.2$; low, $3.2\leq m\leq5$; intermediate or $m\geq5$; and high dispersion). They pointed out that optimal bond thickness becomes more pronounced particularly when m is in intermediate dispersion (i.e., relatively ductile) model. The existence of an optimal bond thickness can be attributed to competition between "number of defects" and stress concentration effects. In the case of overlap length, they have reported that dispersion character of adhesive does not influence the dependence of joint strength on the overlap length, and adhesive joint displays nearly same "limit overlap length".

Burrow et al. [15] used Weibull analysis to determine the reliability of data from bond strengths to dentin measurements as well as tensile tests on resin-based dental restorative materials. With the help of Weibull analysis, they have: (i) determined whether or not the test method has a significant effect on bond test results, (ii) obtained the information related to the overall performance of an adhesive material, and (iii) theoretically modelled the behaviour of materials systems in dental restorations.

In this paper, the authors are concerned with the prediction of mechanical performance and failure characteristics of adhesive joints of dissimilar adherends bonded with relatively brittle adhesive. The authors have also employed the reliability analysis of strength of these joints based upon the statistical Weibull analysis of strength distribution. The effects of stress singularity at the interface corner and scale sensitivity upon strength and failure of brittle adhesive joints will be discussed.

2. Stress singularity based strength prediction

2.1. H_c parameter

Most recently, much attention has been paid to the validation of interface corner failure criterion. Consider an adhesive joint body within linear elasticity context behaviour. When the body is subjected to a remote uniaxial load, the asymptotic stress field develops at the vicinity of interface corners and exhibits singularity behaviour in the form of [16]:

$$\sigma\approx Hr^{-\lambda} \tag{1}$$

where σ is the stress, r is distance from the interface corner, H is intensity of stress singularity and λ is order of stress singularity. The H failure criterion has been originally proposed by Groth [17] and is analogous to the linear elastic fracture mechanics (LEFM) concept, where it is associated with the discontinuity at the interface corner instead of crack. Failure is assumed to initiate at the interface corner when H exceeds the critical value, H_c.

In order for H_c to be a valid failure criterion, any plasticity (i.e., non-linear deformation or failure process zone) must be confined to a small singularity region at the interface corner: condition referred to as small scale yielding theory in LEFM. There are already some experimental evidences, which emphasised that H_c and λ parameters can be effectively used to successfully predict the onset of failure and eventually evaluate the relationship between bond thickness and adherend stiffness, and the strength of certain adhesively-bonded butt and scarf joints [4,18,19]. Hence, the evaluation of λ in such adhesive joints is of technical importance, and this can be fulfilled via adopting the calculation method as performed by Bogy [20]. In this study, the calculation of λ at an interface corner of a bi-material joint was carried out analytically by using Fortran PowerStation 4.0 software (i.e., see Appendix A). The results will be discussed in the following section.

2.2. J_c parameter

H_c parameter which has been explained in the previous subsection is suitable to the problem of adhesive joint without defect. However, for adhesive joint with intrinsic or artificial interfacial crack the application of fracture toughness, J_c parameter as a fracture is seemed to be appropriate. This fracture criterion parameter has the non-dimensional form of a combination of