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Analysis of the adhesively bonded three-point bending specimen for evaluation of adhesive shear behaviour

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ABSTRACT

The adhesive shear stress-strain behaviour is an essential input for the design of structural adhesive joints. Relative to current standard tests, the main advantage of bonded beams is reducing spurious adhesive joint end effects on strength measurements. A beam model was developed in this work for the three-point bending test considering metal adherends, support effects and adhesive elastic-perfectly plastic stress-strain behaviour. Model predictions were in good agreement with finite element analyses for specimens with the thin bondlines typical of structural joints. The present results show that the adhesively bonded three-point bending test can be an interesting approach for the thin bondlines used in structural joints. Nevertheless, there are limitations on the range of measurable properties and data analysis requires models such as the one developed herein.

1. Introduction

Most structural adhesive joints are designed in order to ensure the dominance of shear stresses in the adhesive [1,2]. Measurement of the adhesive shear stress-strain behaviour is thus essential for proper joint design. However, the difficulties in approaching the ideal pure and uniform shear stress state in adhesive joints are well-known. The napkin ring torsion test [3] does approach such requirements and, in principle, can be used to measure the entire adhesive shear stress-strain (τ_a-γ_a) curve with special extensometers. However, this test has not been widely used because of the sensitivity to misalignments and difficulties in bondline thickness control and inner fillets removal [4,5]. Moreover, the napkin ring test demands either torsion testing machines or a special fixture for adaptation to universal testing machines. Although it remains standardised by ISO [6], the former ASTM E229-97 standard was withdrawn in 2003.

The most popular method for measuring adhesive shear properties is nowadays the thick-adherend shear test (TAST), currently standardised by ASTM [7] and ISO [8]. It is basically a single-lap joint in which the thickness of the adherends and the small overlap lengths are designed to minimise peel stresses and τ_a peaks at the ends. The τ_a-γ_a curve can be measured by employing a special extensometer and applying corrections for adherend shear deformations. The TAST was found to yield reproducible results for several types of adhesives e.g. [9,10].

Actually, both of the above methods have the drawback of promoting failure initiation at the joint ends, whose features may influence significantly joint strength. First of all, there is the theoretical problem of the singularity at the adherend/adhesive interface end [11]. Secondly, the true geometry of joint ends involves adherend chamfers or rounded corners, as well as adhesive spew fillets [1]. It has been shown that such features affect TAST results [9,12]. Similar joint end effects exist in other methods such as the solid butt joint torsion test [13], the Iosipescu [14] type butt joint specimen [15,16] and the Arcan [17,18]. Another issue concerning the napkin ring torsion and TAST is the small bonded area, which increases the sensitivity to the aforementioned joint end features and may not provide a sufficiently representative sample of the joints used in practical applications.

A different approach for measuring adhesive properties is testing bulk specimens. Grohs [19] obtained similar τ_a-γ_a curves from bulk Iosipescu and napkin ring torsion specimens. However, the latter had 1 mm thick bondlines, hence much thicker than those commonly employed in structural joints. Burst and Adams [16] compared bulk and butt joint Iosipescu specimens for three aerospace-grade adhesives. Similar moduli and shear strengths were measured without significant bondline thickness dependence [16], but ultimate shear strains were not compared. In both of those studies [16,19] one can identify as limitations the influence of the Iosipescu specimen notch geometry and the small bonded area. Moreover, elaborate manufacturing conditions are needed to avoid high porosity levels in bulk specimens [20,21]. Therefore, the question of the representativeness of measured adhesive properties remains.

Recently, bonded beam tests have been proposed using three-point bending (3PB) [22] or antisymmetric bending [23] setups. In this paper we focus on the former, which is hereafter designated as adhesively bonded three-point bending (AB3PB) test (Fig. 1). It has actually been

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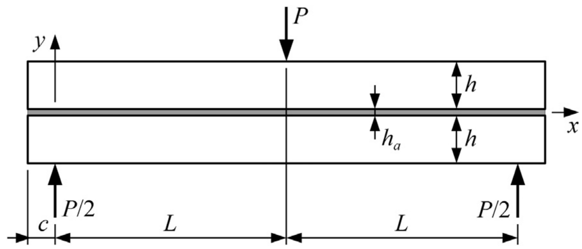

Fig. 1. The adhesively bonded three-point bending (AB3PB) specimen.

used in the form of the short beam shear test [24] or of relatively long beams [22]. In both cases, maximum τ_a occur away from the joint ends, which is a clear advantage over the TAST, Arcan and napkin ring torsion tests. The short beam shear test is currently standardized for measuring an apparent interlaminar strength of polymer matrix composite materials [25]. Further developments involving digital image correlation (DIC) strain field measurements [26], finite element analysis (FEA) and parameter optimization have allowed the extraction of the interlaminar shear stress-strain curve [27]. However, adhesively bonded short beam shear specimens are more sensitive to loading and support roller compression effects and can only generate small regions of nearly constant τ_a [24]. Furthermore, the low shear modulus and non-linear behaviour of polymer matrix composites promote significant adherend shear strains, thereby posing additional difficulties to accurate bondline shear strain measurements.

Longer metal adhesively bonded beams could thus be an interesting simple solution, as recently proposed in [22]. In fact, relatively long specimens are needed to obtain a significant region of nearly constant τ_a, given the effect of the supports and τ_a reversal at half-span. On the other hand, long specimens have higher adherend bending stresses, which may cause premature yielding. Dragoni and Brinson [22] used the beam model developed by Moussiaux [28] to select AB3PB specimen geometries suited either for shear modulus or shear strength measurements of different adhesives. However, the current state-of-the-art in the testing and modelling of adhesive joints demands the measurement of the entire τ_a-γ_a curve, or of a suitable approximation that includes the ultimate strain. Furthermore, the available beam models of the AB3PB specimen did not consider adhesive plasticity, which is an essential characteristic of a structural adhesive. The main objective of this work was precisely to develop a comprehensive beam model of the AB3PB specimen, allowing a more accurate assessment of its potential for evaluating the τ_a-γ_a curve.

2. The beam model

2.1. Adhesive linear elastic behaviour

Let us consider an infinitesimal element of the upper adherend of an AB3PB specimen (Figs. 1 and 2) at a distance $0 < x < L$ from the left support. Besides the normal force N, the transverse shear force V and the bending moment M, the lower surface is subjected to the adhesive layer shear stress τ_a. The present model only considers adhesive shear stresses, which are therefore assumed to dominate the global specimen behaviour, despite inevitable compression stresses in the vicinity of supports and load-point. It is further assumed that τ_a is practically uniform across the bondline thickness h_a, which is clearly a realistic hypothesis for the common bondlines. In this framework, the vertical force and moment equilibrium equations can be written as

$$V = \frac{P}{4} - \frac{bh_a\tau_a}{2} \tag{1}$$

$$V = \frac{dM}{dx} + \frac{bh\tau_a}{2} \tag{2}$$

respectively, where b is the specimen width and h is the adherend thickness (Fig. 1).

It is worth noticing at this stage that, for the typically thin bondlines and stiff adherends, $bh_a\tau_a/2 \ll P/4$ in Eq. (1). Furthermore, the isotropic metal adherends considered in this work, together with the $L/h \geq 9$ geometries here adopted, reduce the contribution of adherend transverse shear to the load-displacement response to levels below 2%. Hence the use of Euler-Bernoulli beam theory,

$$M = EI\frac{d^2v}{dx^2} \tag{3}$$

where E is the adherend Young's modulus, $I = bh^3/12$ is the adherend second moment of area and v is the beam transverse displacement. Nevertheless, a global approximate correction for the effect of transverse shear is introduced below. It is also important to remark that highly localised adherend shear deformations are neglected. This is a realistic assumption for metal adherends, which are much stiffer than adhesives and are subjected to dominant bending moments. Eqs. (1)-(3) can be combined to yield

$$\frac{d^3v}{dx^3} = \frac{3}{Ebh^3}[P - 2b(h + h_a)\tau_a] \tag{4}$$

As for the kinematics, the longitudinal relative displacement u_a of the adherends responsible for the adhesive shear strains results from the bending rotations and axial strains. It is also clear that $(dv/dx)_{x=L} = 0$ and $u_a(L) = 0$, and thus we can write for $x < L$,

$$u_a = -h\frac{dv}{dx} - 2\int_x^L \frac{N}{Ebh}dx \tag{5}$$

an expression that bears the $dv/dx < 0$ and $N > 0$ sign conventions. The linear elasticity and uniform bondline through-thickness γ_a assumptions mean that

$$u_a = h_a\gamma_a = \frac{h_a\tau_a}{G_a} \tag{6}$$

where G_a is the adhesive shear modulus. Moreover, horizontal force equilibrium of the element depicted in Fig. 2 demands that

$$\tau_a = \frac{1}{b}\frac{dN}{dx} \tag{7}$$

After double differentiation of Eq. (5) and substitutions of Eqs. (6) and (7), we have

$$\frac{d^3v}{dx^3} = \frac{2\tau_a}{Eh^2} - \frac{h_a}{G_a h}\frac{d^2\tau_a}{dx^2} \tag{8}$$

which can be combined with Eq. (4) to arrive at the differential equation

$$\frac{d^2\tau_a}{dx^2} - \lambda^2\tau_a = -\lambda^2\tau_R \tag{9}$$

where

$$\lambda = \frac{1}{h}\sqrt{\frac{G_a(8h + 6h_a)}{Eh_a}} \tag{10}$$

is the elastic stress decay parameter and

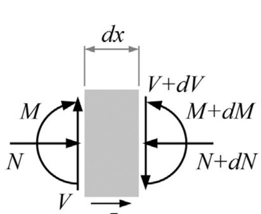

Fig. 2. Forces acting on an infinitesimal element of an AB3PB specimen upper adherend.