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Using the simple peel test to measure the adhesive fracture energy, G_a

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Abstract

The adhesive fracture energy of structural adhesive joints may be readily ascertained from linear-elastic fracture-mechanics (LEFM) methods, and indeed an ISO Test Method (ISO 25217: 2009) now exists for the LEFM Mode I value, G_c, as a result of the efforts of the European Structural Integrity Society (ESIS) 'TC4 Committee' [1,2]. These LEFM test methods involve the preparation and testing of adhesively-bonded double-cantilever beam (DCB) and tapered double-cantilever beam (TDCB) specimens [3,4]. Notwithstanding the sound and reproducible results that may be obtained from such methods, the LEFM test specimens are relatively complex and expensive to make and test, and many industries would far prefer to deduce the value of the adhesive fracture energy from the very common and widely-used 'peel test'. (In the present paper, for clarity, the adhesive fracture energy is termed G_A when deduced from a peel test.) Indeed, the peel test is an attractive test method to assess the fracture performance of a wide range of structural adhesive joints and flexible laminates. However, although it is a relatively simple test to undertake, it is often a complex test to analyse and thus obtain a characteristic measure of the toughness of the adhesive joint, or laminate.

Analysis Strategy

The most successful approach that has been adopted to analysing the peel test is based upon applying a fracture-mechanics method using an energy-balance approach [5-10]. A value of the adhesive fracture energy, G_A, is thereby ascertained; which is the energy needed to propagate a crack through unit area of the joint, either cohesively through any adhesive layer present or along a bimaterial interface. The value of G_A should be characteristic of the joint and, ideally, independent of geometric parameters such as the applied peel angle or the thickness of the flexible substrate arm(s) being peeled. The value of G_A may be obtained via an analytical or a numerical analysis of the peel test. The problems with the latter numerical approach in the present context are that they are invariably complex and are not well-suited for use in an International Standard document [11-14].

The Challenge

The basic problem is that the peel test invariably involves gross plastic deformation of the peeling arm, which may account for up to about 95% of the measured, input peeling energy. This leads to a high degree of accuracy being needed in the analytical or numerical approach being employed to deduce the value of the gross plastic deformation of the peeling arm, which is then subtracted from the measured peeling energy [9,10].

Results

The present paper describes an analytical method for deducing values of G_A from the peel test and considers how it may be applied to both structural adhesive joints and flexible laminates. The value of G_A is ascertained from an energy-balance approach [9,10] and requires the stress versus strain curve of the peel arm to be inputted into the analysis. This can be achieved via (a) a bilinear model, (b) a power-law model or (c) digitisation of the experimental stress versus strain data. A main challenge arises in the case of a flexible, metallic peel arm bonded using a structural adhesive, such as an epoxy adhesive. Since here the measured peel energy, G_{input}, may be a relatively large value and the energy associated with the plastic bending, G_{bend}, of the peel arm may also be relatively large, and to a first approximation: $G_A = G_{input} - G_{bend}$. Now, the subtraction of two relatively large values may well lead to a high scatter being associated with the value of G_A. To reject such data which leads to a high scatter, then a rejection criterion of the correction factor (CF {%} = $100.G_{bend}/ G_{input}$) being ≥85% has been applied. Also, with relatively tough structural adhesives, the maximum strain, e_{max}, at the root of the bending, flexible peel arm must not be so high that the assumptions made in the analysis of the term G_{bend} become invalid. Thus, a second alternative rejection criterion of $e_{max} \geq 4\%$ has also been applied to ensure that only valid data is employed. These aspects are illustrated in Fig. 1. For both rubber-toughened epoxy adhesives, the left-hand side (i.e. 'Before filtering') shows all the values of G_A from replicate tests and the scatter in the data for all these cases is relatively high. (And in all joints cohesive failure through the adhesive layer was observed.) The LEFM G_c value is also given for each adhesive. When the rejection criteria for the values of G_A of CF≥85% or $e_{max} \geq 4\%$ are applied, then the results reduce to those shown on the right-hand side of Fig. 1, termed 'After filtering'. For the moderately tough ESP1110 adhesive, then the scatter associated with the values of G_A from the replicate tests is indeed reduced, but is still relatively high. For the very tough XD4600 adhesive, virtually all the values of G_A from the replicate peel tests are rejected; and the two remaining values of G_A are in poor agreement with the value of G_c from the LEFM tests. It is of interest to note that these observations are independent upon the input method used for the stress versus strain curve of the peel arm. (Again, in all joints cohesive failure through the adhesive layer was observed.)

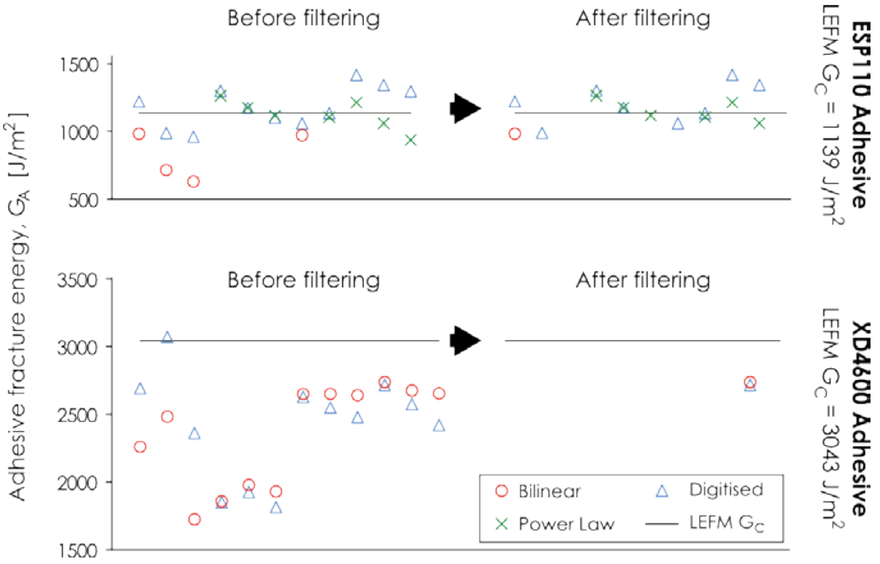

Figure 1. Epoxy-aluminum alloy arm peel joints, with three different input methods used. Before filtering and after applying a rejection criterion. (*Reject data if CF > 85% OR* $e_{max}>4\%$, for the ESP110 adhesive (top) and the XD4600 adhesive (bottom). Cohesive joint failure in all cases.)

The flexible laminate studied was a polypropylene film bonded via a tie-layer to an ethylene vinyl alcohol film, as used by the packaging industry. Tests conducted on the flexible packaging laminates, where the values of the measured peel energy, G_{input}, are relatively low, do not suffer from the problems associated with the structural adhesive peel-joints. This is illustrated in Table 1, where the results from five different laboratories taking part in a 'round-robin' test program are given. Here it may be seen that the values of G_A are relatively low. The values are independent of the peel angle used and of the laboratory where the tests were undertaken. The results also do not depend upon the input method used for the stress versus strain curve of the peel arm.

Table 1. Flexible packaging laminates round-robin results

Lab.	**Input method**	**G_A (J/m^2), peeled at:**		
		45°	**90°**	**135°**
A	Bilinear	57	47	40
A	Power Law	55	52	53
A	Digitised	51	45	43
B	Digitised	58	49	59
C	Bilinear	–	40	–
D	Bilinear	–	47	–
E	Bilinear	–	41	–

Conclusions

Firstly, for the structural adhesive peel joints consisting of epoxy adhesives bonding aluminum alloy and steel substrates the main conclusions were:

(a) Without any ‘rejection criterion’ for rejecting test results where the degree of gross plastic deformation of the peel arm was very excessive, then the ‘Before filtering’ values of G_A have a very large and unacceptable scatter; and are in poor agreement with the LEFM G_c values.

(b) However, the use of a ‘rejection criterion’ did not help very much in getting more reliable and accurate data for the very tough epoxy adhesive peel joints, since almost no data passed the rejection criterion and hence remained to be used to deduce the value of the adhesive fracture energy, G_A.

(c) If one wishes to ascertain the value of the adhesive fracture energy for structural adhesive joints, then the message is very clear: use the LEFM ISO Test Method (ISO 25217: 2009) rather than peel tests.

Secondly, for the adhesive peel joints consisting of flexible laminates, such as packaging or electronic laminates, the main conclusions were:

(a) The use of the peel test gives values of G_A statistically independent of the peel angle, and other geometric details, for the flexible laminates. This is clearly very encouraging.

(b) There is also good agreement between the values from the different laboratories.

(c) The results also do not depend upon the input method used for the stress versus strain curve of the peel arm.

(d) A new ISO standard for determining the value of G_A for flexible laminates from peel tests will be proposed shortly.

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