

GUIDE TO THE USE OF DATA ITEMS IN THE DESIGN OF BONDED JOINTS

1. INTRODUCTION

This Item provides guidance on the use of the analytical procedures presented in Data Item Nos 79016 and 80039 as aids in the design of bonded joints. It relates the Items to the principal complementary or alternative methods currently available and provides examples of the adhesive material properties required for use with the Items and recommendations on how to obtain such properties. Finally it draws attention to important factors affecting joint strength not covered by the analytical procedures and supplies references as a source of further information.

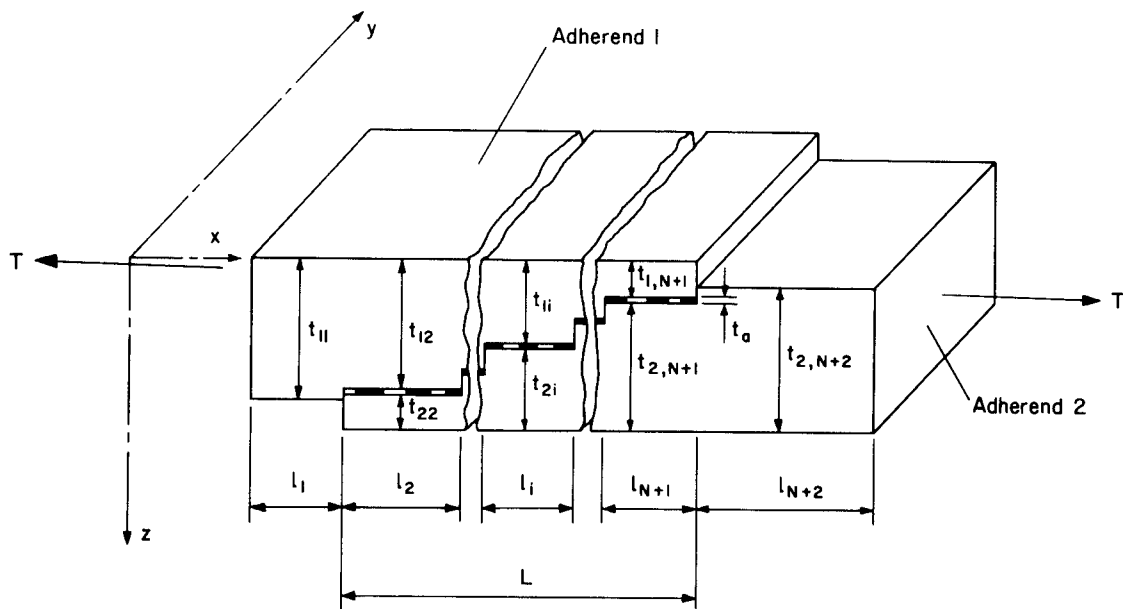
2. NOTATION

D	external diameter of napkin ring specimen	m	in
d	internal diameter of napkin ring specimen	m	in
E_a	effective modulus of elasticity of adhesive material	N/m ²	lbf/in ²
E_1, E_2	moduli of elasticity of materials of adherends 1 and 2, respectively, in x-direction	N/m ²	lbf/in ²
f_a	direct stress in adhesive material in z-direction	N/m ²	lbf/in ²
G_a	shear modulus of adhesive material	N/m ²	lbf/in ²
i	zone number		
l_i	length of i th zone (i varies from 1 to $N + 2$)	m	in
L	total bonded length (zone 2 to $N + 1$)	m	in
N	number of bonded (overlapping) steps in joint		
q_A	shear stress to which theoretical stress-strain curve of adhesive is asymptotic (defined in Data Item No. 79016)	N/m ²	lbf/in ²
q_a	shear stress in adhesive in plane of joint	N/m ²	lbf/in ²
q_{av}	average shear stress in adhesive ($= T/L$)	N/m ²	lbf/in ²
q_E	shear stress in adhesive at elastic limit	N/m ²	lbf/in ²
q_F	shear stress at which cohesive failure occurred in adhesive under test	N/m ²	lbf/in ²
T	tensile load on joint per unit width, half load on double lap joint	N/m	lbf/in
t_a	thickness of adhesive layer, constant	m	in
t_{1i}, t_{2i}	thickness at zone i of adherends 1 and 2, respectively, where i varies from 1 to $N + 2$	m	in

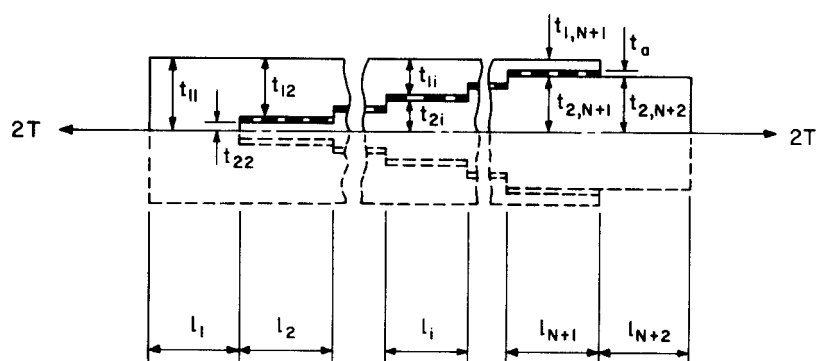
U_1, U_2	deformation of adherends 1 and 2, respectively, adjacent to adhesive layer, in x -direction	m	in
W	width of thick adherend specimen	m	in
x	in-plane coordinate along joint length		
y	in-plane coordinate across joint width		
z	out-of-plane coordinate, normal to plane of joint		
γ	shear strain in adhesive ($= (U_2 - U_1)/t_a$)	m/m	in/in
γ_E	shear strain in adhesive at elastic limit	m/m	in/in
γ_F	shear strain at which cohesive failure occurred in adhesive test	m/m	in/in
γ_{max}	maximum value of γ for particular joint and applied loading	m/m	in/in
ν_{1x}, ν_{1y} ν_{2x}, ν_{2y}	Poisson's ratios for material of adherends 1 and 2 loaded in x - and y -directions, respectively		

Direct Stress Convention: tensile stresses are positive, compressive stresses are negative.

Both SI and British Units are quoted but any coherent system of units may be used.



Sketch 2.1 Geometry of asymmetric stepped lap joint



Sketch 2.2 Geometry of symmetric (double) stepped lap joint

3. DATA ITEM NOS 79016 AND 80039 IN RELATION TO OTHER ANALYTICAL METHODS

In order to make the most efficient use of the Data Items it is necessary to understand their limitations and helpful to know their relationship to the other principal analytical methods currently available. The theoretical analysis of the adhesive stresses in bonded joints has developed from the early work of Volkersen (Reference 1) and Goland and Reissner (Reference 2). Reference 1 considered the shear lag effect that results from the differential straining of the adherends under in-plane load, producing shear stress concentrations at the ends of the lap joint. Reference 2 incorporates the effect of bending in the joint due to the offset load, which results in direct stresses normal to the plane of the joint (peel stresses).

Data Item No.79016 introduces a computer program that provides an analysis of the inelastic adhesive shear stresses and strains and elastic adherend direct in-plane stresses in single or double multistep lap joints. Being based on the shear lag analysis of Reference 18 it does not take account of the normal direct stresses in the joint but does allow for the inelastic properties of the adhesive, representing them by a non-linear idealisation that provides a close approximation to the actual adhesive curve. It is therefore comparable to the stepped lap analysis of Reference 8. Data Item No. 80039 introduces a computer program that provides an elastic analysis of the shear and normal direct (peel) adhesive stresses in single and double multistep lap joints (see Sketch 2.1). Therefore it can only be directly compared to any of the other references in its single step form. In Figures a and b the analyses of the adhesive shear stresses in a four step double lap joint as determined by Item Nos 79016 and 80039 are compared. Data Item Nos 78042 and 80011 provide the results of parametric studies for particular configurations analysed using Data Item Nos 79016 and 80039, respectively.

Most current theoretical analyses have been concerned with developments of the methods in Reference 1 and, particularly, Reference 2. In Reference 2 elastic solutions were obtained for a single step lap joint under in-plane tension load, having similar (balanced) adherends, for the cases where (a) the adhesive has negligible effect on joint flexibility and (b) joint flexibility is mainly due to the adhesive. Subsequent developments have reduced the approximations assumed in References 1 and 2 and catered for different joint configurations (for example: double lap joints, unbalanced adherends and stepped joints).

A particular limitation of the theory in case (b) of Reference 2 is that it neglects the transverse (normal) and shear flexibilities of the adherends which can be significant factors in resin based composite materials. This limitation is remedied in References 19, 23 and 33 for elastic symmetric and asymmetric single lap joints (single step).

Extensive analyses of bonded joints are outlined in Reference 5 and detailed in References 6, 7 and 8. For each of a number of joint configurations a suitable approximate solution is adopted. These references contain inelastic shear stress analyses combined, for appropriate configurations, with elastic normal direct stress analyses (bending effects). In these analyses the shear stress-strain curve of the adhesive is idealised as two straight lines, one elastic and one plastic (horizontal), positioned to match the maximum plastic stress and strain and the strain energy of the actual adhesive curve. Joint efficiencies are judged in relation to three possible failure modes: (1) adherend failure under direct in-plane stress, (2) adhesive cohesive failure under shear stress and (3) adherend failure under normal direct stress (peel). Balanced and unbalanced single and double lap joints (single step) are considered in References 6 and 7. Reference 8 considers balanced and unbalanced scarf joints and stepped lap joints though the normal direct (peel) stresses in stepped lap joints are neglected. Fortran computer program listings are provided in each of References 6, 7 and 8.

A number of finite element analyses of bonded lap joints exist (for examples see References 18 and 26) which are useful for specialised design and comparative purposes but currently have limited application in general design for economic reasons.

4. COMPARISON OF ANALYTICAL METHODS AND THEIR RELEVANCE IN JOINT DESIGN

All the analytical methods available in the references contain some degree of approximation. Generally the complexity of the solutions means that a choice has to be made between accuracy of solution and practicality of joint idealisation. The more rigorous the solution the less complex the joint configuration it can be applied to and vice-versa.

For single step joints fairly rigorous solutions are available (References 19, 23 and 33) that provide elastic analyses for balanced and unbalanced (thick adherend) lap joints catering for the shear and normal flexibilities of composite adherends and that may be developed to allow for inelastic adhesives. Such single step joints however are severely limited in their load carrying capacity and where high loads are to be carried more complex joint configurations should be considered.

The balanced scarf joint has a more uniform stress distribution and because of this is theoretically a more efficient joint (Reference 8), particularly for thick adherend applications in which the peel stresses in single lap joints can be critical. While there are suitable applications for scarf joints they can however present manufacturing problems and rapidly lose their efficiency when dissimilar adherends are to be joined (for example metal to composite). Stepped lap joints tend towards a uniform stress distribution (see Figure 3a) and therefore approach the efficiency of scarf lap joints but are generally easier to manufacture, particularly when laminated, composite adherends are to be used. Multistep joints consequently represent a particularly practical configuration and are covered by Data Item Nos 79016 and 80039 and by Reference 8. Though more approximate in the elastic range than the previously mentioned analyses of single lap joints the Data Items can aid the design of stepped lap joints in two ways, even when composite adherends are involved. The likely effect of changing geometry or materials can be judged in terms of reduction of stresses or load carrying capacity. In addition, by choosing the appropriate analysis, conservative estimates of the most critical stresses can be made.

A direct comparison of results obtained using the analyses of Data Item Nos 79016 and 80039 is made in Figure a by showing the shear stress distribution along the lap joint when the peak shear stress is q_E . In Figure b the effect of considering the inelastic shear properties of the adhesive is illustrated by giving the distributions when the peak shear stress is q_F , using the elastic analysis of Data Item No. 80039, and when $\gamma = 0.1$ and γ_F , using the inelastic analysis of Data Item No. 79016. This figure shows clearly the importance of considering the inelastic properties of the adhesive. The load levels in the figure demonstrate, for this particular joint, the likely excess carrying capacity remaining in the adhesive if designed for a peak strain of $\gamma_{max} = 0.1$ when the nominal failure strain $\gamma_F = 0.5$. However, this potential should be used with caution as adhesive properties vary considerably with environment and time.

The differences in the stress-strain behaviour of different adhesives or an adhesive in different environments can mean that, for a particular joint configuration, an adhesive with a high failure stress, q_F , may be able to take less load than a more ductile adhesive with a lower failure stress. Figure 2 shows the loads that produce peak stresses and strains equivalent to the failure stresses and strains of three different adhesives in the same basic single step joint. The figure shows that the relative load carrying capacities of the three adhesives change as the length of the joint varies and that the nominally lower strength adhesives can take the higher static load.

Figures 3a and 3b demonstrate, respectively, the decrease in the peak elastic stresses and increase in load carrying capacity ($\gamma_{max} = 0.1$) obtained by increasing the number of steps in the joint. Figure 8 of Item No. 79016 demonstrates the effect of changing the adherend materials on the shear stresses in a series of 6-step lap joints in each of which $\gamma_{max} = 0.1$.

While bonded joints can fail in a number of ways the most common forms of failure in statically loaded bonded joints are:

- (1) adherend failure at the joint extremities,
- (2) adhesive cohesive failure,
- (3) peel at the end of an adherend and/or delamination in composite joints,
- (4) adhesion failure at the interface of the adherend and the adhesive.

The Data Items can be used directly in assessing the likelihood of failure in the first three modes. Mode (4) is greatly influenced by such factors as surface preparation and bonding techniques and the relevant allowable strength data are not provided in the Data Items.

The direct in-plane stress in the adherend, which is the dominant consideration in assessing adherend failure at the joint extremities ((1) above), is given by Data Item No. 79016 in the form of a distribution throughout the joint length. Both cohesive failure in the adhesive ((2) above) and adherend peel failure ((3) above) occur as a result of combined shear and direct stresses; in each case Data Item Nos 79016 and 80039 can assist in assessing the behaviour of the dominant stress. Reference 26 has shown that in practical joints with spew at the joint end cohesive failure in the adhesive is likely to start under the influence of combined stress in the spew and develop into a shear failure along the joint.

While therefore failure criteria may vary as the crack progresses, the dominant factor is the shear stress in the adhesive. The distribution of this shear stress can be obtained using either Data Item No. 79016 or Data Item No. 80039. The results from the two Data Items will differ slightly. Data Item No. 79016 should be used for highly loaded, balanced, joints as it allows for adhesive plasticity but not for bending effects. Data Item No. 80039 should be used for unbalanced joints as it allows for the bending effects, though it will not allow consideration of adhesive plasticity. In considering adhesive peel failure or delamination of composite adherends at the ends of the joint ((3) above), the dominant consideration is the magnitude of the normal direct stresses. These can be assessed, in the region of elastic adhesive behaviour, with the aid of Data Item No. 80039.

In applying the analyses provided in Data Item Nos 79016 and 80039 the following points ought to be borne in mind. The analyses provided in the Data Items do not allow for the transverse (normal) flexibility of the adherends which is important for the interlaminar bonding of composite adherends. References 5 to 8 indicate that the peel stresses are likely to be less critical when the outer adherend is comparatively thin and that a more efficient joint can be obtained by varying the step length along the joint. Since Data Item No. 79016 is based on a shear lag analysis, it will be less reliable where there is significant imbalance and Data Item No. 80039 should then be used.

5. TEST METHODS FOR OBTAINING ADHESIVE MATERIALS PROPERTIES

The adhesive materials properties required for use with Data Item Nos 79016 and 80039 are a complete shear stress-strain curve and G_a and E_a , respectively. Most of the analyses in the references have similar requirements. Examples of the materials properties of various adhesives are given in Section 6. However, in most circumstances it is advisable for the user to obtain the materials properties of the adhesive to be used taking account of conditions of storage and service (see also Section 7).

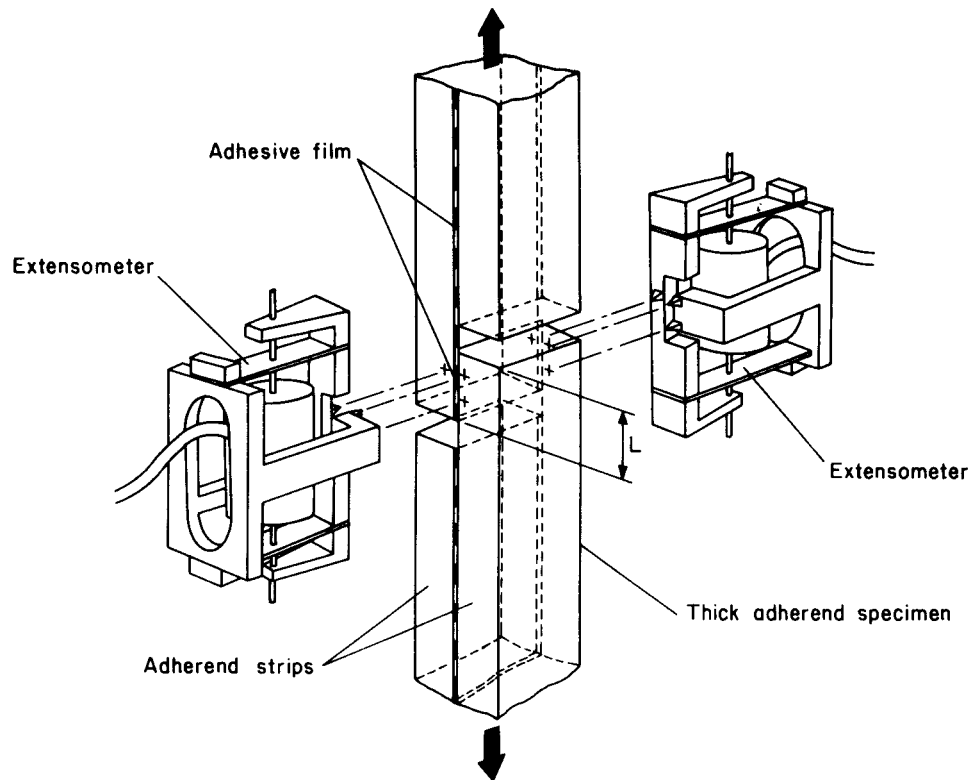
Single lap tensile test specimens that are currently recommended in standards to establish adhesive strength and provide quality control do not give the required adhesive properties because of their complex adhesive stress pattern (References 5, 19, 24, 30). A number of different test methods have been devised to obtain the shear and tensile properties of adhesives and these are extensively examined in Reference 30 and surveyed in Reference 24. The present Data Item makes recommendations as to the most suitable tests so that the user may make a selection according to individual requirements.

Two basic test configurations are recommended as alternatives for obtaining shear stress-strain data, and therefore G_a , for adhesives:

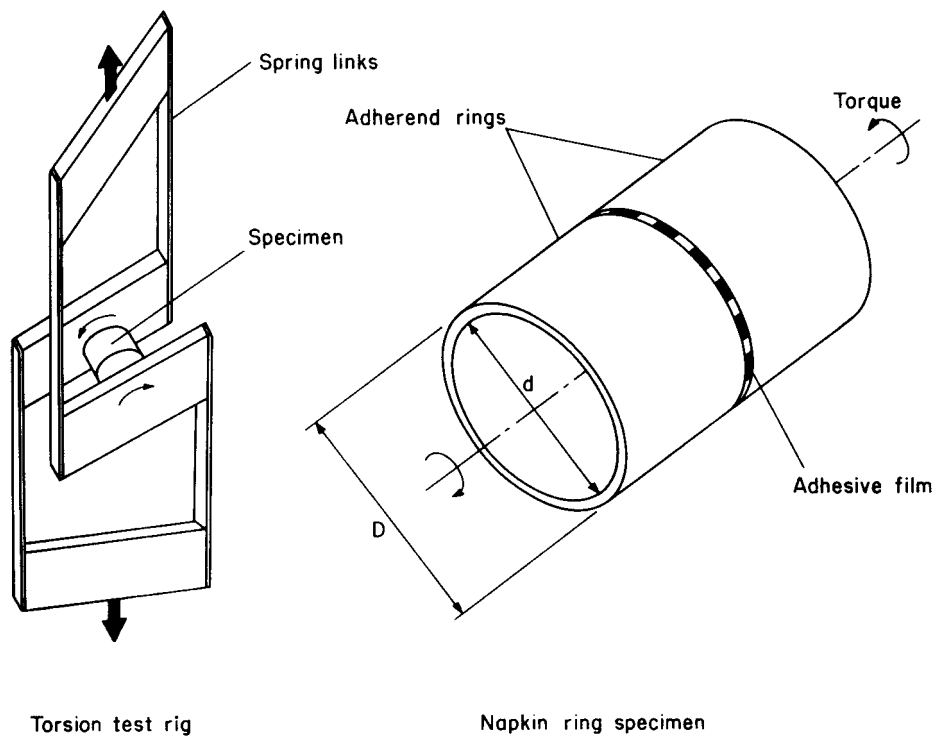
- (1) the thick adherend test,
- (2) the torsion test.

Sketch 5.1 illustrates the KGR-1 extensometer devised to perform the thick adherend test (1). A detailed specification of this apparatus is given in Reference 17. An alternative form of thick adherend test is suggested in Reference 31 that uses a different form of extensometer and shorter bonded test length.

Sketch 5.2 illustrates the test specimen and test rig for a napkin ring torsion test (2). A detailed specification of this test is given in Reference 40. An alternative specification for napkin ring tests is given in Reference 11.



Sketch 5.1 Thick adherend test (KGR-1 extensometer, Reference 17)



Sketch 5.2 Torsion test (Reference 40)

Figure 4 shows a comparison of shear stress-strain curves for the adhesive FM-73 obtained by both thick adherend methods and a Napkin ring torsion test (see Reference 32).

Both of the test systems recommended have advantages and disadvantages and these can be summarised as follows.

TABLE 5.1

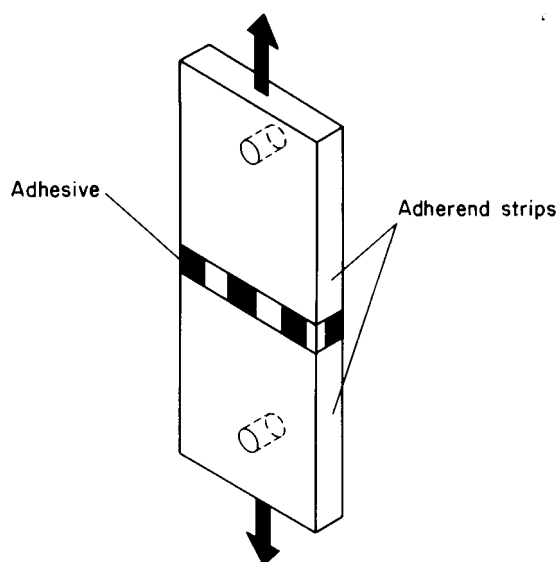
<i>Napkin Ring/Round Bar Specimen</i>	<i>Thick Adherend Specimen</i>
<i>Advantages</i> (1) Measures (virtually) the absolute properties. (2) Pure shear loading, self-aligning. (3) Simple correction of the adherend deflection. <i>Disadvantages</i> (4) Expense of making numerous specimens. (5) Sensitivity to test environment conditions. *(6) May be difficult to control glue line thickness (particularly for low viscosity adhesives). *(7) Non standard test rig.	<i>Disadvantages</i> (1) Measures average of a distribution having stress concentrations. (2) Complexity of loading alignment. (3) Non-uniform adherend stress makes accurate extensometer positioning necessary. <i>Advantages</i> (4) Lends itself to quantity production, modest cost. (5) Robust specimens easy to test. (6) Glue line thickness easily controlled. (7) Fits standard test machine. (8) Good simulation of actual structural element.

From Table 5.1 it can be seen that the thick adherend tests are likely to be most suitable for industrial use and that torsion tests will be more suitable for use in Universities or research establishments where points *(6) and *(7) are unlikely to present difficulties.

In addition to the points in Table 5.1, the following points should be considered when obtaining the shear stress-strain data. First the rate of testing is significant. Figure 5 shows the effect of different rates of loading on the stress-strain curves for the adhesive AF 126-2 (Reference 31). Similar curves are given in Reference 35. A pause during test is likely to produce a creep step. Tests should ideally be conducted at a constant strain rate rather than a constant load rate; a typical testing time is about 2 minutes. Specimen preparation is particularly important as deficiencies in surface adhesion and inclusions within the adhesive can lead to premature failure. The glue line thickness should be measured as accurately as possible.

When conducting the tests it will be necessary to separate the deflection of the adherends from that of the adhesive. This is achieved by testing a solid specimen of the adherend material. In thick adherend tests the load alignment should be checked. Composite adherends should not be used in the tests.

The test methods recommended to establish the tensile properties of adhesives, in particular the modulus of elasticity, E_a , are either bulk tensile specimens or butt specimens (see Sketch 5.3). Bulk specimens are likely to be more difficult to manufacture than butt specimens. The optimum configurations for butt specimens are considered in Reference 30. Where the adhesive and adherend plastic strain rates are significantly different the effect of the transverse restraint applied by the adherend to the adhesive will vary throughout the test.



Sketch 5.3 Tensile test butt joint specimen (Reference 30)

Any programme of shear and tensile tests performed should consider the storage and operating environments of the adhesive as the adhesive properties will vary considerably with temperature, moisture content and time (see Section 7).

6. ADHESIVE MATERIALS PROPERTIES

The material properties data currently available for use with Data Item Nos 79016 and 80039 and other analyses vary considerably in quality. It is therefore advisable to perform tests to obtain the required data, as recommended in Section 5.

In this section examples of the adhesive shear stress-strain curves and values of G_a and E_a are given. The data given are for tests at room temperature. The shear properties have been obtained from either thick adherend or napkin ring torsion tests. The tensile properties have been obtained from bulk or butt joint specimens. Figures 6 to 9 give the adhesive shear stress-strain curves, while the moduli G_a and E_a are given in Tables 6.1 and 6.2.

It is stressed that these data are given as examples only. The properties of adhesives vary considerably with test conditions and working environment (see Section 7).