

Guide to the use of Data Items in the design of bonded joints

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

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

1. INTRODUCTION

This Item provides guidance for using the analytical procedures presented in ESDU 79016* and ESDU 80039† which examine the elastic and inelastic stresses in the adhesive of bonded lap joints loaded in tension and shear. This Item also discusses the alternative methods currently available to determine such stresses and how the required adhesive properties can be obtained. Many factors known to affect the strength of bonded joints and methods (other than analytical procedures) are also considered in this Item.

ESDU 78042‡ gives experimentally derived stress-strain curves that enable the estimation of average shear stress corresponding to the peak shear strains in the adhesive layers in a double lap joint. A general introduction to adhesives and the design of bonded joints can be found in the related Item ESDU 18008** which discusses the mechanical, geometrical and aesthetic advantages of adhesively bonded joints.

2. NOTATION

D	external diameter of napkin ring specimen	m	in
d	internal diameter of napkin ring specimen	m	in
E_a	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	elastic 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 ESDU 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

* ESDU 79016, 'Inelastic shear stresses and strains in the adhesives bonding lap joints loaded in tension or shear'.

† ESDU 80039, 'Elastic adhesive stresses in multistep lap joints loaded in tension'.

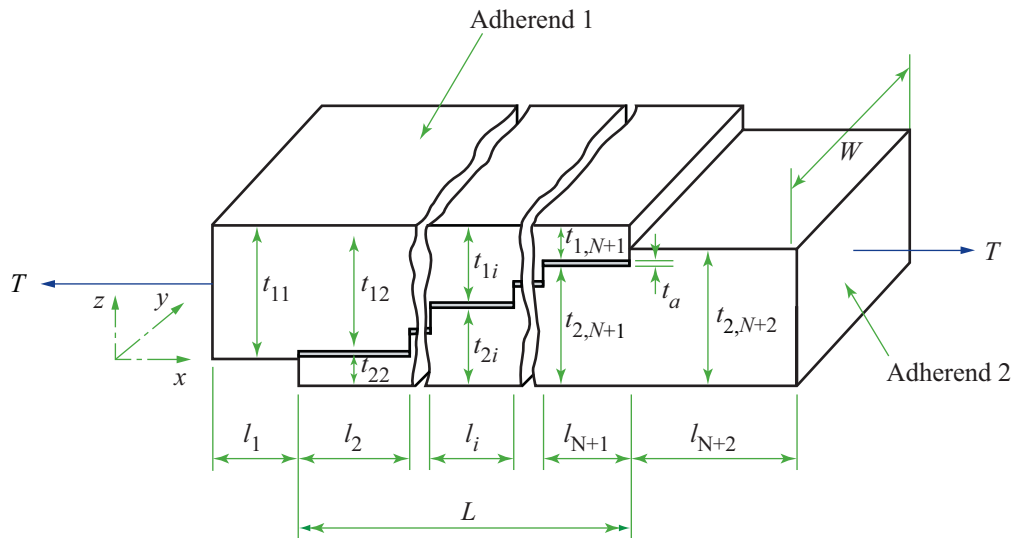
‡ ESDU 78042, 'Shear stresses in the adhesives in bonded joints. Single step double lap joints loaded in tension'.

** ESDU 18008, 'An overview of bonded joint design'.

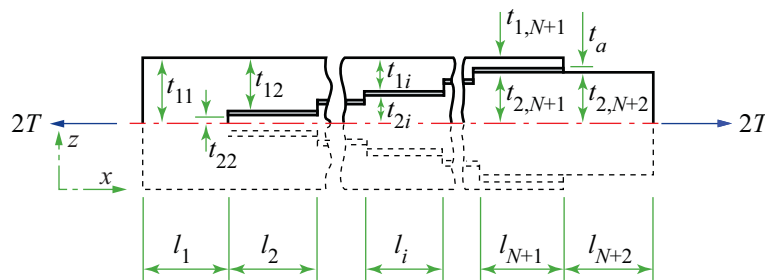
q_F	shear stress at which cohesive failure occurred in adhesive under test	N/m ²	lbf/in ²
T	load per unit joint width	N/m	lbf/in
t_a	thickness of adhesive layer, constant	m	in
t_{1i}, t_{2i}	thickness at zone i of adherends 1 and 2, respectively, where i varies from 1 to $N + 2$	m	in
U_1, U_2	deformation of adherends 1 and 2, respectively, adjacent to adhesive layer, in x -direction	m	in
W	width	m	in
x	in-plane co-ordinate along joint length		
y	in-plane co-ordinate along joint width		
z	out-of-plane co-ordinate, 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. ESDU 79016 AND 80039 IN RELATION TO OTHER ANALYTICAL METHODS

In order to make the most efficient use of ESDU 79016 and ESDU 80039, it is necessary to understand their limitations and it is also helpful to know their relationship to the other principal analytical methods that are currently available. The theoretical analysis of adhesive stresses in bonded joints has developed based on early work by Volkersen (Derivation 1) and Goland and Reissner (Derivation 2). Derivation 1 considered the shear lag effect that resulted from the differential straining of the adherends under in plane load, producing shear stress concentrations at the ends of the lap joint. Derivation 2 incorporated the effect of bending in the joint due to the offset load, which resulted in direct stresses normal to the plane of the joint (peel stresses).

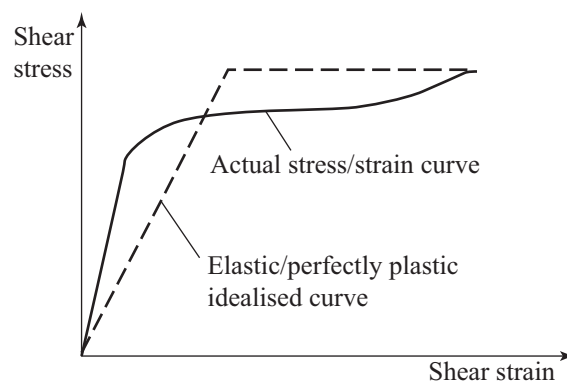
ESDU 79016 presents a computer program to analyse the inelastic adhesive shear stresses and strains and elastic adherend direct in-plane stresses in single or double multistep lap joints. Being based on the shear lag analysis of Derivation 18, ESDU 79016 does not take account of the normal direct stresses in the joint but it does allow for the inelastic properties of the adhesive by representing them as a non-linear idealisation that gives a close approximation to the actual adhesive strength curve. It is therefore comparable to the stepped lap analysis of Derivation 8. ESDU 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 1a and 1b the analyses of the adhesive shear stresses in a four step double lap joint as determined by ESDU 79016 and 80039 are compared. ESDU 78042 and ESDU 80011*, Elastic stresses in the adhesive in single step double lap bonded joints, provide the results of parametric studies for particular configurations analysed using ESDU 79016 and ESDU 80039, respectively.

Most analytical analyses are based on developments from the methods in Derivation 1 and, particularly, Derivation 2. The elastic solutions in Derivation 2 are for a single step lap joint under in-plane tension load having similar (balanced) adherends, and 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 Derivations 1 and 2 and also cater for different joint configurations (for example: double lap joints, unbalanced adherends and stepped joints).

A particular limitation of the theory in case (b) of Derivation 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 Derivations 19, 23 and 33 for elastic symmetric and asymmetric single lap joints (single step).

Extensive analyses of bonded joints are outlined in Derivation 5 and detailed in Derivations 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, elastic and perfectly plastic (horizontal), which are positioned to match the maximum plastic stress and strain and the strain energy of the actual adhesive curve (see Sketch 3.1). Balanced and unbalanced (in terms of adherend stiffness or thickness) single and double lap joints (single step) are discussed in Derivations 6 and 7. Derivation 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 Derivations 6, 7 and 8.



Sketch 3.1 Idealisation of an example adhesive shear stress/strain curve

A number of finite element analyses of bonded lap joints exist (for examples see Derivations 18, 26 and 42) which are useful for specialised design and comparative purposes.

* ESDU 80011, 'Elastic stresses in the adhesive in single step double lap bonded joints'.

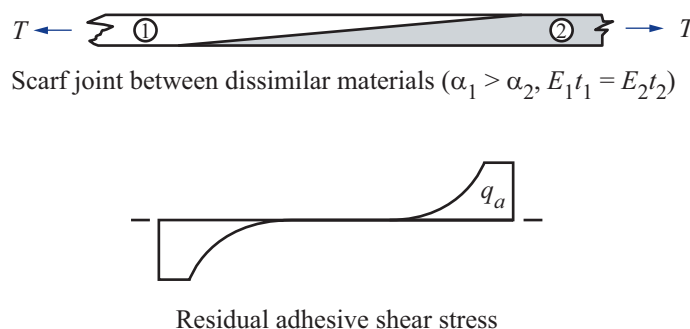
4. COMPARISON OF ANALYTICAL METHODS AND THEIR RELEVANCE IN JOINT DESIGN

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 the accuracy of solution and the practicality of joint idealisation. The more rigorous the solution the less complex the joint configuration it can be applied to, and vice-versa.

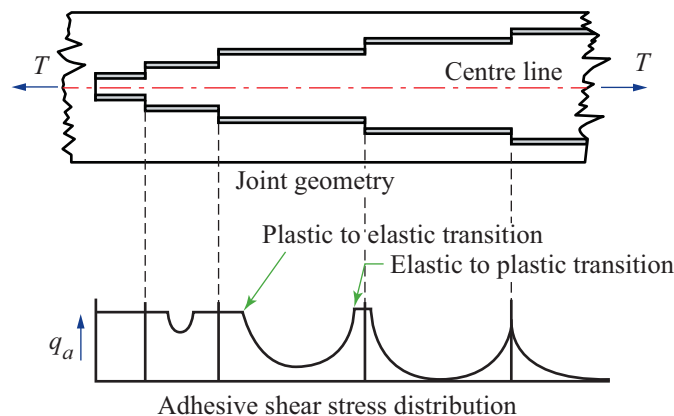
For single step joints, rigorous solutions are available (Derivations 19, 23 and 33) that provide elastic analyses for balanced and unbalanced (thick adherend) lap joints catering for the shear and normal flexibilities of composite adherends. These solutions may be developed to allow for inelastic adhesives. Such single step joints are, however, severely limited in their load carrying capacity and if high loads are to be carried then more complex joint configurations should be considered. During design, the level of allowable stress in the adhesive layer at the maximum load during service life of the joint is generally established from the ultimate tensile strength multiplied by a safety factor (Derivation 41).

The balanced scarf joint has a more uniform stress distribution and because of this is theoretically a more efficient joint (Derivation 8), particularly for thick adherend applications in which the peel stresses in single lap joints can be critical. While there are many applications for scarf joints they can, however, present manufacturing problems and lose their efficiency when dissimilar adherends are joined (for example, metals to composites). This is a particular problem when the coefficients of thermal expansion of the materials in the joint are different and when the manufacturing temperature is not the same as the working temperature of the joint consequently causing a large variation in residual stresses, see Sketch 4.1.

Stepped lap joints tend towards a uniform stress distribution and approach the efficiency of scarf lap joints but are generally easier to manufacture, particularly when laminated or composite adherends are used, Sketch 4.2. Multistep joints present a particularly practical configuration and are covered by ESDU 79016 and ESDU 80039 and by Derivation 8. Though more approximate in the elastic range than the previously mentioned analyses of single lap joints, these Data Items 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 the load carrying capacity. In addition, by choosing the appropriate analysis then conservative estimates of the most critical stresses can be made.



Sketch 4.1 Residual adhesive shear stress in a bonded scarf joint between dissimilar materials with a thermal mismatch (Derivation 8)



Sketch 4.2 Adhesive shear stresses in a bonded stepped-lap joint using similar materials (Derivation 8)

A direct comparison of results obtained using the analyses of ESDU 79016 and ESDU 80039 is made in Figure 1a by showing the shear stress distribution along the lap joint when the peak shear stress is q_E . In Figure 1b the effect of the inelastic shear properties of the adhesive is shown by the distributions when the peak shear stress is q_F , using the elastic analysis of ESDU 80039, and when $\gamma = 0.1$ and when $\gamma = \gamma_F$, using the inelastic analysis of ESDU 79016. Figure 1b 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 load carrying capacity that remains 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 the adhesive properties may vary considerably with environment and time.

The differences in the stress-strain behaviour of different adhesives or an adhesive used 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 which are equivalent to the failure stresses and strains of three different adhesives in the same basic single step joint. This figure confirms that the relative load carrying capacities of the three adhesives change with the joint length 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 7 of ESDU 79016 shows that changing the adherend materials will alter 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 given in Table 4.1.

TABLE 4.1

		For further information, see:
(1)	cohesive failure of the adhesive	ESDU 79016, ESDU 80039
(2)	adhesion failure at the interface of the adherend and the adhesive	—
(3)	peel at the end of an adherend and/or delamination in composite joints	ESDU 79016, ESDU 80039
(4)	adherend failure at the joint extremities	ESDU 79016

Note that failure type (2) is influenced by such factors as surface preparation and bonding techniques but the relevant allowable strength data are not provided in this or in other Data Items.

ESDU 79016 considers the distribution of shear stress in the adhesive resulting from the transmission of direct in-plane stress from one adherend to another via the adhesive when assessing adherend failure at the joint extremities (failure type (4)). Both cohesive failure in the adhesive (failure type (1)) and adherend peel failure (failure type (3)) happen because of combined shear and direct stresses; in each case ESDU 79016 and ESDU 80039 assess the behaviour of the dominant stress. Derivation 26 shows that for practical joints with spew at the joint-end (note that spew is a fillet of adhesive which is squeezed out under pressure whilst the joint is being formed), cohesive failure in the adhesive starts because of the combined stress in the spew and then develops into a shear failure along the joint.

In practice, failure starts as one or more of the Fracture Mechanics Modes of cracking (as described in Section 3 of ESDU 80036*), and then often continues in a different Mode. This means that the failure criteria may vary as the crack progresses but the dominant factor is the shear stress of the adhesive. The distribution of shear stress can be found using ESDU 79016 or ESDU 80039 but the results from the two Data Items will differ slightly: ESDU 79016 should be used for highly loaded, balanced, joints as it allows for adhesive plasticity but not for bending effects, and ESDU 80039 should be used for unbalanced joints as it includes the bending effects though it does not allow for adhesive plasticity.

For adhesive peel failure or the delamination of composite adherends at the joint ends (failure type (3)), the dominant cause is the magnitude of the normal direct stresses and these can be assessed, in the region of elastic adhesive behaviour, using ESDU 80039.

In applying the analyses provided in ESDU 79016 and ESDU 80039 the following points ought to be borne in mind. The Data Items do not allow for the transverse (normal) flexibility of the adherends which is important for the interlaminar bonding of composite adherends. Derivations 5 to 8 show that the peel stresses are less critical in joints where the outer adherend is thinner. Since ESDU 79016 is strictly based on a shear lag deformation analysis, it is less reliable if there is significant imbalance in geometry and/or material properties of the joint, in such cases ESDU 80039 should be used.

* ESDU 80036, 'Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components'.