

# An overview of bonded joint design

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## AN OVERVIEW OF BONDED JOINT DESIGN

### CONTENTS

|                                                                | Page         |
|----------------------------------------------------------------|--------------|
| <b>1. INTRODUCTION</b>                                         | <b>1</b>     |
| <b>1.1 NOTATION</b>                                            | <b>1</b>     |
| <b>2. SELECTION OF ADHESIVES AND ADHERENDS</b>                 | <b>2</b>     |
| <b>2.1 Background</b>                                          | <b>2</b>     |
| <b>2.2 Adhesives</b>                                           | <b>3</b>     |
| <b>2.3 Materials</b>                                           | <b>4</b>     |
| <b>2.3.1 Surface preparation</b>                               | <b>5</b>     |
| <b>2.3.2 Surface treatment</b>                                 | <b>6</b>     |
| <b>2.4 Adhesive Bonding Versus Traditional Joining Methods</b> | <b>6</b>     |
| <b>3. JOINT DESIGN, LOADS AND STRESSES</b>                     | <b>7</b>     |
| <b>3.1 Design</b>                                              | <b>7</b>     |
| <b>3.2 Loading</b>                                             | <b>8</b>     |
| <b>3.3 Stresses in bonded joints</b>                           | <b>9</b>     |
| <b>4. FAILURE OF BONDED JOINTS</b>                             | <b>13</b>    |
| <b>4.1 Common Modes of Failure</b>                             | <b>13</b>    |
| <b>4.2 Effect of Temperature</b>                               | <b>15</b>    |
| <b>4.3 Effect of Moisture</b>                                  | <b>15</b>    |
| <b>5. SUMMARY</b>                                              | <b>15</b>    |
| <b>5.1 Design Considerations</b>                               | <b>15</b>    |
| <b>5.2 Advantages of Adhesively Bonded Joints</b>              | <b>16</b>    |
| <b>5.3 Disadvantages of Adhesively bonded joints</b>           | <b>17</b>    |
| <b>6. DERIVATIONS</b>                                          | <b>18</b>    |
| <b>7. WORKED EXAMPLE</b>                                       | <b>21</b>    |
| <b>8. TABLES AND FIGURES</b>                                   | <b>22</b>    |
| <b>8.1 Tables</b>                                              | <b>22</b>    |
| <b>9. FIGURES</b>                                              | <b>26-30</b> |

## AN OVERVIEW OF BONDED JOINT DESIGN

### 1. INTRODUCTION

This Item provides information on, and guidance for, the design of adhesively bonded joint including the use of other ESDU Data Items related to this subject\*.

Adhesives can be used to join two materials together to produce a strong bond of smooth appearance. A background to bonding science and terminology is given in Section 2. In recent years, adhesive bonding has become more usual in manufacturing meaning that the use of adhesives to join components for structural, semi structural and non-structural engineering applications in the automotive, electronics, aerospace and construction industries has expanded greatly. The adhesives considered in this Data Item are epoxies, polyurethanes (PU) and methyl methacrylate (MMA) types that are frequently used to bond common reasonably stiff engineering materials, such as metals, plastics, ceramics or composites, or any combination of these, see Section 2. Section 2 also compares adhesive bonding to more traditional joining methods such as bolting, riveting or welding as well as using adhesives alongside these joining methods to form a hybrid joint.

The most common design of an adhesively bonded joint is a lap joint but adhesives can also be used in T-joint, corner joints and tubular joints as well as to join irregularly shaped surfaces. A well selected adhesive in the bonded joint should evenly distribute externally applied loads along the full length of the joint thereby reducing any stresses and resisting external flexing and vibration stresses, see Section 3. The modes of failure likely to occur in adhesively bonded joints are discussed in Section 4.

There are clearly many advantages to selecting adhesives to bond two materials, even when other joining methods are available, such as simplicity, cost and the ability to join problematic materials together. However, there are also several limitations when choosing an adhesive to bond. A full consideration of the advantages and disadvantages of an adhesively bonded joint is given in Section 5.

A worked example is provided in Section 7.

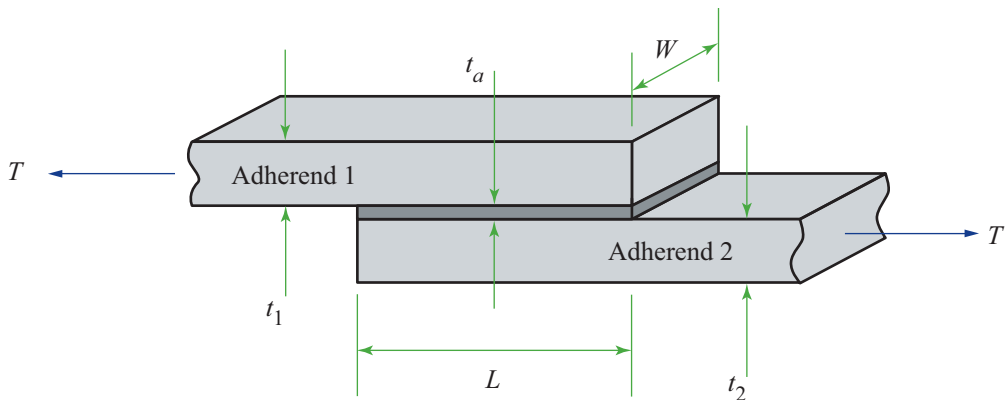
### 1.1 NOTATION

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

|            |                                                                      |                  |                     |
|------------|----------------------------------------------------------------------|------------------|---------------------|
| $E$        | modulus of elasticity of adherend                                    | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $E_1, E_2$ | moduli of elasticity of materials of adherends 1 and 2, respectively | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $G_a$      | shear modulus of adhesive                                            | N/m <sup>2</sup> | lbf/in <sup>2</sup> |

\* ESDU 92041, 'Stress analysis of single lap bonded joints (adhesive and adherends)'.  
 ESDU 17004, 'Guide to use of Data Items in the design of bonded joints'.  
 ESDU 80039, 'Elastic adhesive stresses in multistep lap joints loaded in tension'.  
 ESDU 80011, 'Elastic stresses in the adhesive in single step double lap bonded joints'.  
 ESDU 79016, 'Inelastic shear stresses and strains in the adhesives bonding lap joints loaded in tension or shear'.  
 ESDU 78042, 'Shear stresses in the adhesives in bonded joints. Single step double lap joints loaded in tension'.  
 ESDU FAT E.05.07, 'Endurance of bonded double strap joints. (Aluminium alloy sheet material; phenolic resin/vinyl powder glue, tensile loading.)'.  
 ESDU FAT E.05.06, 'Endurance of bonded lap joints. (Aluminium alloy sheet material; phenolic resin/vinyl powder glue, tensile loading.)'.

|               |                                                                       |                  |                     |
|---------------|-----------------------------------------------------------------------|------------------|---------------------|
| $L$           | total bonded length                                                   | m                | in                  |
| $p$           | coefficient used in Equation (3.2)                                    |                  |                     |
| $T$           | tensile load on joint per unit width, half-load on a double lap joint | N/m              | lbf/in              |
| $t$           | thickness of adherend                                                 | m                | in                  |
| $t_a$         | thickness of adhesive layer, constant                                 | m                | in                  |
| $t_1, t_2$    | thicknesses of adherends 1 and 2, respectively                        | m                | in                  |
| $W$           | width                                                                 | m                | in                  |
| $\gamma$      | shear strain in the adhesive                                          |                  |                     |
| $\tau$        | shear stress                                                          | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $\tau_a$      | average shear stress in adhesive                                      | N/m <sup>2</sup> | lbf/in <sup>2</sup> |
| $\tau_{\max}$ | maximum shear stress                                                  | N/m <sup>2</sup> | lbf/in <sup>2</sup> |



Sketch 1.1 A bonded joint

2. SELECTION OF ADHESIVES AND ADHERENDS

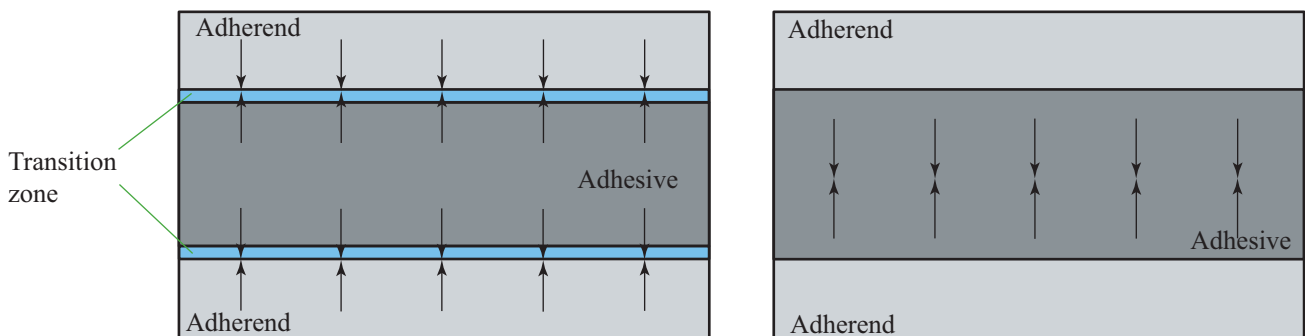
2.1 Background

Adhesion is the property of an adhesive substance to join materials by surface attachments (see Sketch 2.1 a) using one of the following mechanisms:

- specific adhesion, which depends principally on the action of van der Waals forces between the molecules of the adhesive and surface layers of the materials (adherends) being joined, or
- mechanical adhesion, in which the adherends are to some extent keyed together by molecular filaments of the adhesive that penetrate into the adherend (*i.e.* into the surface and those regions close to the surfaces of the adherends), Derivation 11.

The mechanical and optical properties in the adhesive are altered in the vicinity of the interface with the adherend in a so-called ‘transition zone’ which can have a thickness of anywhere from a few nanometres up to a couple of millimetres.

Cohesion is the internal strength in the adhesive and is the result of the various interactions within the adhesive (Sketch 2.1b). In the cohesion zone, the adhesive possesses its nominal properties, determined by molecular forces, such as the viscosity of the adhesive and the strengthening of bonds during curing, as specified by the adhesive manufacturer. Note that the adhesive strength must be sufficiently high, and this is the case when the natural strength of the adhesive, and not the adhesion, is the limiting factor in strength tests.



**Sketch 2.1 (a) Adhesion – the attractive forces between dissimilar surfaces and (b) cohesion – the internal strength of the adhesive**

The strength of an adhesive is characterised by the force required to pull the adhesive cleanly from the adherend. Both adhesion (including the transition zone) and cohesion affect the bond strength. High toughness and shear strength of the adhesive are essential to maintain the good bond strength brought about by flow of the adhesive and wetting (the process of establishing full coverage of the contact area between the adhesive and the adherend).

## 2.2 Adhesives

The main structural adhesives considered in this Data Item, each with different structural and physical characteristics, are the following types.

- Epoxy adhesives are used for bonding metals and stiff components such as thermoset plastics or composites and have excellent durability, chemical and temperature resistance with little shrinkage.
- Polyurethane adhesives are more suitable for thermoplastics and due to their flexible properties are generally used with softer materials.
- Methyl methacrylate (MMA), or acrylic, adhesives provide good adhesion onto metals, composites and thermoplastics and tend to be faster setting so improving productivity.

Each of these types of adhesive is available as a ‘one-part’ or a ‘two-part’ system. The ‘one-part’ adhesive polymerises and hardens after application at room temperature, and the polymerisation process can be accelerated at higher temperatures. The ‘two-part’ adhesives consist of two substances which, when mixed, begin to co-polymerise until a strong, tough, heavily crosslinked adhesive is formed, and again this process can be accelerated at high temperatures (Derivation 11), see Table 8.1.

'Two-step' acrylic adhesives are cured through contact with an activator typically applied to one of the surfaces to be bonded while the adhesive is applied to the other. The selection of an activator depends on the adhesive curing time, its effect on bond strength, the time it spends on the adherend before the joint is assembled and the form in which the activator is provided (Derivation 31).

A comparison of the room temperature lap-shear strength and the peel strength per unit width of certain adhesives is given in Table 8.2. Surface preparations, pre-treatments or additives combined with the adhesive (such as a rubbery addition to improve the toughness of brittle adhesives) may be used to increase adhesion.

Structural adhesives, such as epoxies and certain acrylics, can also carry large stresses in structural applications (Derivation 24). They are also very strong when used below their glass transition temperatures (the temperature at which the polymer, particularly in an epoxy, changes from a soft, rubbery material to a hard, glassy material).

Semi-structural adhesives are used when failure is not so critical, for example:

- Pressure sensitive adhesives are elastomers which have a very low modulus and can deform easily under small pressures allowing them to wet surfaces.
- Hot-melts become liquid when heated, wetting the surfaces and then cooling to become a solid polymer.
- Anaerobic adhesives cure within narrow spaces deprived of oxygen and are often used to lock bolts or bearings in place (Derivation 24).

Non-structural adhesives, such as contact adhesives, are applied for aesthetic purposes when cost-effective means are required for assembly of finished products (Derivation 24).

## 2.3 Materials

Many engineering materials can be adhesively bonded, as well as composite materials that are now widely used across the aerospace industry (Derivation 25). The adhesives used for aerospace components not only have to meet new technical specifications, but they also have to comply with tougher environmental and safety criteria, such as the ASTM D3762\* wedge crack durability test (Derivation 30). A trial of adhesively bonding steel (0.6 mm thickness) for vehicle bodies reported favourable results using adhesives compared to spot welding, with the bonded joints showing better deformation behaviour, damping performance and fatigue performance (Derivation 26).

ESDU E.05.06 and ESDU E.05.07 provide fatigue data for bonded lap, or bonded double strap joints, respectively, using aluminium alloys with a phenolic resin/vinyl powder glue under tensile loading. The fatigue strength of the bonded joint was found to depend markedly on the local stress distribution and on sheet (adherend) failures. For tests carried out at various mean stress levels, the normal trend for aluminium alloys is observed but for the adhesive failure, the effect of mean stress is negligible.

Table 8.1 lists the adhesives and the materials that can readily be bonded.

\* ASTM D3762, 'Standard test method for adhesive-bonded surface durability of aluminium (wedge test)', ASTM, West Conshohocken, PA, 2010.

The surface preparation and surface treatment of materials before adhesion usually involves one or more procedures such as cleaning and physical or chemical modification to enhance bonding and also to (Derivation 34):

- remove or prevent the later formation of a weak layer on the surface of the adherend,
- maximize the degree of molecular interactions between the adhesive, or primer, and the adherend surface,
- optimize the adhesion forces that develop across the interfaces therefore ensuring sufficient initial joint strength and also strength during the lifetime of the bond, and
- create a specific surface microstructure on the adherend.

## 2.3.1 Surface preparation

For plastic adherends, surface preparation is aimed at increasing the polarity match of the adherends to the adhesive thereby improving surface wetting and creating preferable sites for the adhesive to bond to. The surfaces of metal adherends are typically covered with an oxide layer that must be removed before bonding to improve the bond durability, especially if it is exposed to humid conditions (Derivation 34).

Degreasing, which is suitable for most materials, is a process to remove any traces of oily contaminants and grease from the adherend surface before bonding. This practice includes vapour degreasing, water and ultrasonic degreasing (Derivation 34).

Abrasion can be used to roughen the adherend surface therefore increasing the surface contact area before bonding. This method is usually followed by some degreasing to ensure that any remaining particles are removed. One example of an abrasion process is grit-blasting which will remove tarnish, rust or mill scale from metals. If the component to be bonded is thin, then a wire brush, emery cloth or sandpaper can be used instead of grit-blasting (Derivation 34).

Standard D2651\* covers the surface preparation of wrought metals including aluminium alloys, stainless and carbon steels, titanium alloys, magnesium alloys and copper and its alloys. Due to the wide variety of individual alloys and their heat treatments, the fact that certain adhesives behave differently with surface preparation and also the complex nature of some of the components being bonded, this standard recommends that preliminary tests be carried out with the specific adhesive and the exact metals to determine performance. This is especially true for stainless steel. The adhesive manufacturers' recommendation should also be considered.

The surface preparations that need to be considered before bonding carbon steel, low alloy steels and stainless or corrosion resistant steels are cleaning, descaling, rust and oxide removal and passivation (for stainless steels only), see Derivation 33.

For aluminium, copper and its alloys, abrasion treatments such as sandblasting and hand sanding produces surfaces with good initial bonds but these may not always give durable bonds. A ferricchloridenitric acid process should produce stronger joints for non-ferrous metals (Derivation 33).

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\* D2651-01(2008), 'Standard Guide for Preparation of Metal Surfaces for Adhesive Bonding', ASTM.

## 2.3.2 Surface treatment

Surface treatment of adherends before bonding can include mechanical processes (*e.g.* grinding, jet-cleaning), chemical processes (for metals: *e.g.* etching; for plastics: *e.g.* gas-phase fluorination) and physical processes (for plastics: low pressure plasma) that alter the structure and/or the chemical composition of the surface, see Table 8.3 and Figure 1.

To obtain a high-quality reproducible strong bond the adherend surfaces must have good wetting properties so, for example, the chosen adhesive should not form into beads but distribute itself (spread) evenly across the surface. Also, the surface layer of the adherend must be securely attached to the component (for example to avoid rust forming in a moisture-rich environment) and have good bonding properties, such as the intermolecular and chemical interactions it has with the adhesive molecules.

Figure 2 and Table 8.4 show the maximum strength, reproducibility and durability of an adhesive bond after using either a chemical etch or an anodizing surface treatment. Note that the exposure time to this chemical treatment is important because if it is too short then the surfaces would not be sufficiently activated, whilst overexposure builds up a layer of chemical reaction that may interfere with the bonding. There are also health and safety implications (Derivation 34).

Figure 2 shows how various surface treatments impact the durability of aluminium bonded joints under adverse (hot/wet) conditions. The components that had acid pickling or the anodizing surface treatments before bonding are shown to have a greater peel strength compared to mechanical surface preparations such as abrasion using Scotchbrite or shot blasting using alumina grit (Derivation 8).

A surface post-treatment may be used to preserve the treated surface of the adherends before bonding, or can be applied as a primer, activator or as an adhesive powder before the adhesive is applied to improve the joint quality.

## 2.4 Adhesive Bonding Versus Traditional Joining Methods

Other methods of joining materials, such as welding, brazing, riveting or bolting, (see other ESDU Data Items\*), may not be applicable and might introduce unfavourable stresses in the joint or even weaken the assembly. For cases such as these, a structural adhesive can be used instead to produce a bond, or the adhesive could be used alongside another joining method to form a 'hybrid joint'. Some advantages of using adhesives compared to other joining methods are given below.

- Adhesive bonding easily joins dissimilar materials and modern materials, such as plastics, composites and porous materials.
- The adhesive can bond and seal all in one operation.
- The bond enhances the structural strength of the assembly without significantly increasing the weight.
- The stresses in a correctly designed bonded joint will be distributed evenly, thus improving the joint integrity and fatigue resistance (see Section 3).
- Adhesive bonding reduces, or can completely eliminate, the occurrence of galvanic corrosion.

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\* ESDU 67008, 'Elastic stresses in single lap joints under tension or compression'.  
ESDU 86013, 'Guide to the use of Data Items on the fatigue strength of welded joints in steels'.  
ESDU 92041, 'Stress analysis of single lap bonded joints (adhesive and adherends)'.  
ESDU 14003, 'Guide to bolted joints and screw threads data'.

- There is no distortion in the completed assembly such as that which can be caused by welding heat input.
- Adhesive bonds produce aesthetically pleasing assemblies without any further refinishing costs.

There are many reported instances of using rivets alongside adhesives to form a hybrid joint which has greater strength, higher maximum load carrying capacity and better stiffness than the bonding or riveting methods alone (Derivations 18, 23 and 29). Using rivets in an adhesive joint means that if bond failure occurs, the joint behaves as with the rivets only.

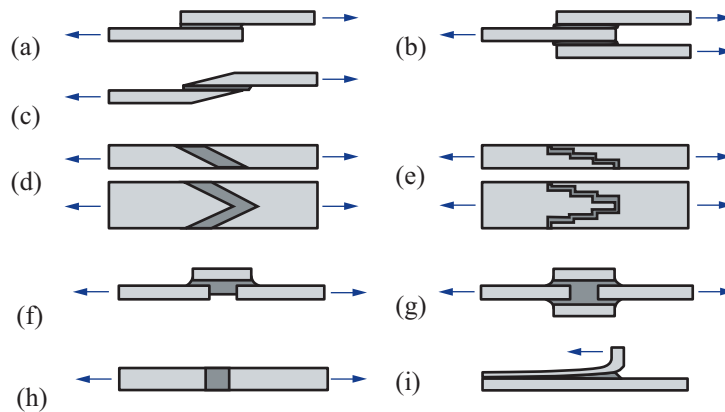
In a bolted-bonded hybrid joint, the bolts were found to reduce stresses at the edge of the overlap, especially after the initiation of failure (Derivations 16 and 17). Table 8.5 summarises the advantages and disadvantages of bonding versus bolting joints in composites (Derivation 25).

It has been shown that stress peaks in bonded joints can be reduced by positioning a spot weld in the overlap after the adhesive has been applied but before hardening of the adhesive layer (Derivation 19). In such welded-bonded hybrid joints, adhesives that have a low Young's modulus are recommended for larger bond-line thicknesses, and also in welded-bonded joints between dissimilar materials, the addition of the adhesive layer increases the joint strength and provides a better distribution of stresses in the joint (Derivation 20 and 21).

### 3. JOINT DESIGN, LOADS AND STRESSES

#### 3.1 Design

Many adhesively bonded joints use an overlap to increase the load per unit width ( $T$ ) carrying capacity of the joint and the simplest design is a single or a double lap joint, see Sketch 3.1a and 3.1b. Axial load is transferred from one adherend to the other through the shear in the adhesive only over a finite length meaning that any increase in the overlap length would not necessarily increase the joint strength. The tapered single lap joint (a scarf or bevel joint) is more efficient than the standard lap joint under tensile loading as the tapered edges allow bending of the joint under stress (Sketch 3.1c and 3.1d). The stepped joint gives a more uniform stress distribution in the load bearing area of the joint, however this design requires more machining and is not always feasible for thinner materials (Sketch 3.1e). Butt straps are used to improve the strength and durability of a joint (Sketch 3.1f and 3.1g). The tensile properties of the adhesive joint tend to be poor. The tensile strength of an adhesive bond can be tested using a butt joint, Sketch 3.1h. A corner joint, as shown in Sketch 3.1i, has the bending moment applied to the upper end of the rightangled plate however this may lead to peel or cleavage stresses. See Section 3.2 for further information regarding the likely stresses in the joints shown in Sketch 3.1.



**Sketch 3.1 Common types of lap joints: (a) single lap, (b) double lap, (c) bevel, (d) scarf, (e) stepped, (f) butt strap, (g) double butt strap, (h) butt and (i) corner joint**

## 3.2 Loading

It is likely that an adhesively bonded joint in service may experience one or more of the following sets of load conditions:

- peel loads produced by out-of-plane forces acting on thin adherends.
- shear stresses due to tensile, torsional or pure shear loads on the adherends.
- bending stresses created by out-of-plane tensile loads.
- cleavage loads produced by out-of-plane tensile loads acting on stiff, thick adherends at the joint ends.

When planning an adhesive joint, the design of the joint need not necessarily be the same as that for other joining methods such as welding, bolting *etc.* The intrinsic properties of an adhesive means that it will work better under shear or compressive loading, compared to when a peel or cleavage load is applied, see Sketch 3.2. In practice though, the bonded joint may experience several types of loading at once meaning that a correctly designed bonded joint should maximise the area over which the external load is applied to minimise the stress.

It is recommended that joints which behave poorly under cleavage stress be recessed using a tongue and groove configuration such as the scarf joint or the stepped joint. Angle or corner joints can also experience peel or cleavage stresses therefore, depending on the thickness of the adherends, the joint design may be modified to reduce the effect of these forces, see Sketch 3.2.