Chapter

Mechanical Strength of Adhesively Bonded Metals

António B. Pereira and Alexandre Luiz Pereira

Abstract

Adhesive joints are nowadays widely used in fields ranging from packaging to aeronautics. Nevertheless, the absence of accurate failure criteria remains an important obstacle that often prevents the use of adhesive joints in structural applications. The main objective of this work is to be an introduction to the subject, and it was for this to evaluate the factors that most influence the strength of overlap adhesive joints.

Keywords: adhesive joints, overlap adhesive joints, strength of adhesive joints

1. Introduction

Glued joints currently have a wide range of applications, from the packaging industry to the demanding aeronautical industry. The characteristics of the so-called structural polymeric adhesives allow the increasing use of primary adhesive joints, that is, connections whose performance is critical for the integrity of the structure in which they are inserted. Among the main advantages of glued joints, we can mention:

- high mechanical strength if the joint is well designed
- weight and number of parts savings compared to bolted and riveted connections
- minimization of corrosion problems, especially in the connections of different materials
- sealing and thermal insulation capacity
- vibration dampening, due to the viscoelastic behavior of the glues
- good resistance to fatigue, to which the absence of holes and the respective stress concentration effect strongly contribute
- good esthetic appearance
- the fact that they are often the cheapest option.

Glued joints are particularly interesting for joining advanced high-strength materials, such as polymer matrix composites. Alternative riveted and bolted connections are much less efficient than metallic materials due to the low ductility and poor crush strength of composites.

Adhesive joints, however, have several limitations:

- the current difficulties in the rigorous design of joints, which lead to the adoption of empirical methods or rather conservative calculation processes
- sensitivity to cleavage loads
- need for cleaning and surface preparation procedures
- the time it may take to develop strength (curing time for thermosets)
- some inspection difficulties
- impossibility of dismantling without destroying the joint
- sensitivity to environmental exposure (temperature, humidity, UV radiation, etc.) and creep.
- **Figure 1** shows the main types of adhesive joints. The most used are single-lap and double-lap joints. Stair and ramp joints have high performance and are mainly applied in aeronautics for parts made of composite materials with a relatively high thickness (above 5 mm) [1]. The manufacturing costs of these joints are much higher than the costs of overlap joints.

Adhesive joints load can be ordered in three main ways, namely (1) shear; (2) tensile; and (3) cleavage (**Figure 2**).

A fundamental principle in the design of bonded connections is that the adhesive should preferentially transmit shear forces. Cleavage loads are highly harmful. Tensile demands are also to be avoided, as unavoidable misalignments cause cleavage efforts.

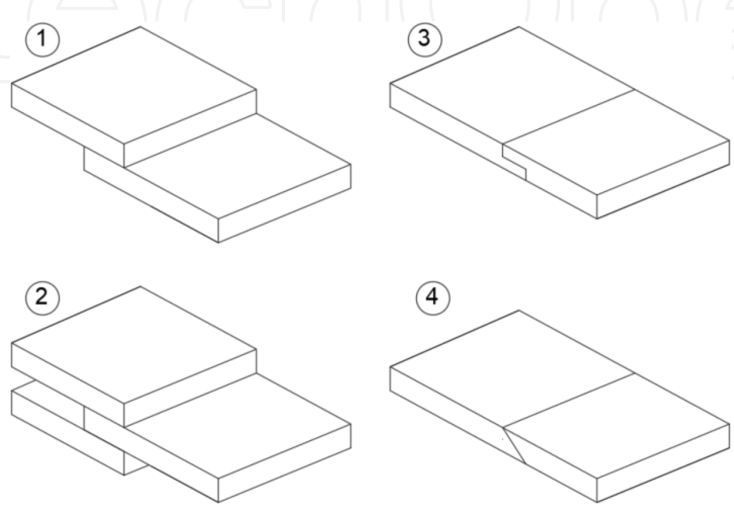

Figure 1.
The most common types of glued joints: (1) single-lap; (2) double-lap; (3) stair; (4) ramp.

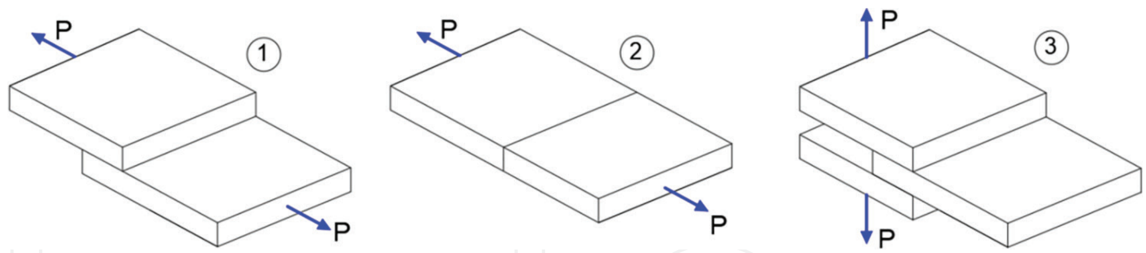

Figure 2.
Fundamental loading ways: (1) shear; (2) tensile; (3) cleavage.

It should be noted, however, that, in the overlap joints, there are always localized cleavage stresses.

Joint failure can occur in three ways:

- adhesive breakage, that is, by detachment at one of the adherent/adhesive interfaces
- cohesive rupture of the adhesive
- fracture of one of the adherents.

One of the main causes of adhesive breakage is inadequate surface preparation [2]. The specific action of the preparation normally consists of:

- increasing the surface roughness, in order to promote mechanical contact with the adhesive
- cause chemical changes that favor electrostatic attraction at the atomic level, through van der Waals forces.

The procedures naturally depend on the materials to be connected and are often the subject of standards, which are particularly well established for several metal alloys [3, 4]. The first stage of the preparation is cleaning the surfaces, especially in terms of degreasing, using solvents, detergent solutions, trichloroethane vapor (toxic), ultrasound, etc. The surface roughness can be increased by applying fine abrasive paper or by shot blasting, after which it is necessary to remove the loose particles. In the case of metals, it is recommended to carry out a chemical attack with appropriate solutions, or even electrochemical treatments, as is the case of anodizing Al alloys. The application of primers favors the durability of the connection.

Several studies have already been presented on the effect of surface preparation on failure mode and on the strength of bonded joints [2, 5]. The conclusions, however, do not always go in the same direction, either in terms of failure modes or in terms of the classification of surface treatments. In [5] it is considered that the interfacial rupture is due to deficient bonding procedures, namely inadequate preparation or contamination of the surfaces. However, in [6], where a vast amount of experimental results of glued Al joints were reviewed, there were cases of interfacial ruptures even when sophisticated treatments were used. Interfacial ruptures even seem to be quite frequent after more or less prolonged exposure to environments of relatively high temperature and humidity. In a large-scale study carried out in Japan [7], frequent adhesive failures were observed in joints with steel adherents. However, according to [5], there are cases of apparent interfacial rupture in which more sophisticated analysis methods allow us to verify the presence of a very thin adhesive layer on the fracture surfaces.

Another factor to be controlled is the thickness of the adhesive layer, for which there is an optimal range, generally between 0.1 and 0.3 mm [8]. The strength of the joint decreases markedly with the thickness of the adhesive layer above certain values, due to the greater probability of the existence of defects. On the other hand, thicknesses that are too thin considerably increase the risk of failure of the adhesive layer. Thickness control can be done through the clamping devices used in the gluing operation. In other cases, small glass spheres can be added to the adhesive that guarantee a certain thickness. The use of adhesives in the form of films allows better control of the thickness of the joint, although with generally higher costs.

Finally, the proper choice of adhesive is critical to joint performance. Structural adhesives are normally thermosetting polymers, as thermoplastics are more susceptible to creep and property degradation from environmental exposure. The most common types of adhesives are epoxides, polyurethanes, modified acrylics, and cyanoacrylates. Epoxy adhesives are the most used, given their good chemical resistance and good creep behavior. There is a great variety of formulations, which are relatively fragile based on, but which become very ductile with the addition of rubber or thermoplastic particles. Curing generally takes place at temperatures between 20 and 120°C, so heating means may be required. Polyurethane adhesives cure by reaction with ambient humidity, have excellent toughness and moderate cost. Resistance to environmental exposure and creep are the main limitations, which are shared by acrylic adhesives, said to be modified, as they are derived from thermoplastic formulations. These, however, have good cleavage strength, moderate cost, and are less demanding in surface preparation. Cyanoacrylates cure quickly and have good cleavage strength, but bond durability is relatively low.

2. Characterization of adhesives

The characterization of the behavior of the adhesives is somewhat delicate. In fact, the most common tests of adhesive joints do not directly provide the mechanical properties of the adhesives, having mainly a comparative or quality control value. Cleavage assays are clearly in this category. **Figure 3(1)** and **(2)** represent the two most common specimens, specified by ASTM D 1876 [9] and ASTM D 3762 [10], respectively. In the first case, the force necessary to progressively break the joint is

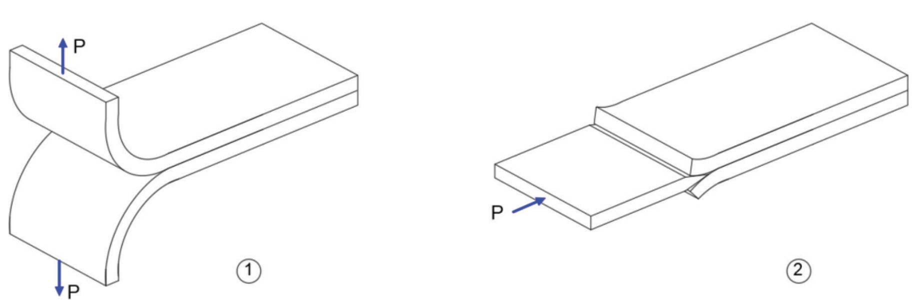

Figure 3.
Adhesive joint cleavage tests: (1) ASTM D1876; (2) ASTM D3762.

measured, while in the second test, the advance of the crack in the joint relative to the position of the wedge is normally measured. These tests only allow comparing adhesives and/or surface preparation techniques, as well as evaluating the effect of environmental exposure.

The shear test of simple overlap joints is also widely publicized at ASTM D 1002 [11] standard for metals (**Figure 4**).

The overlap length L is determined in such a way that there is no yielding of the adherents before the joint breaks, since it is intended to measure the ultimate stress at the average shear of the adhesive. Once again, this test has only comparative value, as it does not allow measuring the true shear strength of the adhesive. In fact, the distribution of the shear stress along L is not uniform (**Figure 5**). On the other hand, the eccentricity of the load causes bending of the adherents (**Figure 6**) and cleavage stresses at the ends of the bond.

The tests that allow obtaining the mechanical properties of the adhesives are more complex. The shear strength can be obtained from the so-called "thick tack" test (ASTM D 5656) [12]. It is again a simple overlap joint with 9.5 mm thick adherents to minimize bending deformations and cleavage stresses. The overlap length L is proportionately small (9.5 mm), so that the shear stress distribution is approximately uniform. The use of a strain gauge also makes it possible to obtain the shear modulus of the adhesive, Ga.

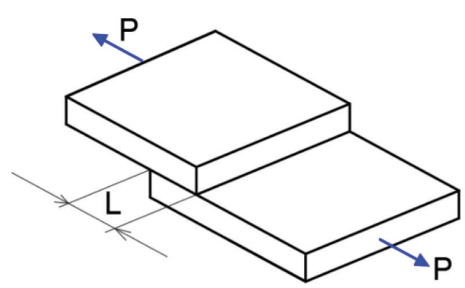

Figure 4.
ASTM D 1002-10 test sample.

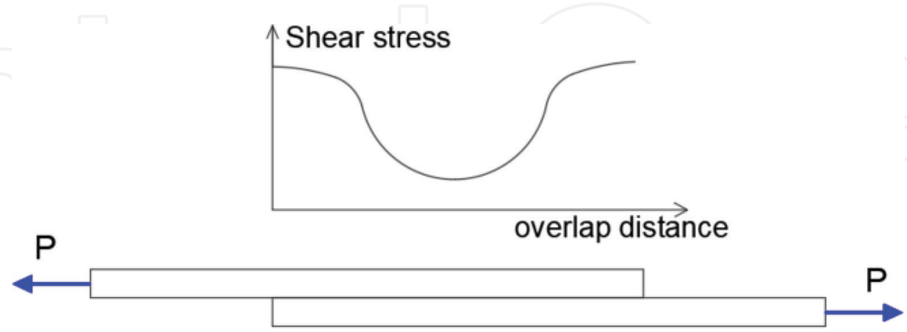

Figure 5.
Distribution of shear stresses in a lap joint.

Figure 6.
Bending effect on a simple lap joint.

3. Strength of overlap adhesive joints

There are important difficulties in the design of glued joints. In stress analysis, there is a singularity in the adherent/adhesive interface that makes it difficult to use the stresses obtained with Finite Element (FE) models. Therefore, simplified analyses are normally used, which, despite the inevitable limitations, are still recommended by design codes [13]. These analyses apply mainly to joints with adherents in tensile mode. **Figure 7** shows the case for single-lap joint in shear.

The best-known analysis is that of Goland-Reissner [14], which takes into account the effect of bending in the simple lap joint, but which is clearly unrealistic in assuming linear elastic behavior for the adhesive. Instead, the Hart-Smith analysis [15] considers the plasticization of the adhesive through an elasto-perfectly plastic approach.

In either case, the fundamental dimensioning parameter is the overlap length L. This must be sufficient to prevent failure due to cleavage stresses and that the average shear stress is too high, promoting excessive creep deformations. However, beyond a certain value, there is no advantage in increasing L, as it penalizes the joint in terms of weight without any gains in joint strength. At this stage, the difficulty lies in the absence of a sufficiently stringent failure criterion. Hart-Smith [15] found that, in the short term, joints can reach breaking loads close to the smallest of the following values:

$$P_1 = \sqrt{2\tau_p t_a \left(\frac{\gamma_e}{2} + \gamma_p\right) E_i t_i \left(1 + \frac{E_i t_i}{E_o t_o}\right)} \tag{1}$$

$$P_2 = \sqrt{2\tau_p t_a \left(\frac{\gamma_e}{2} + \gamma_p\right) E_o t_o \left(1 + \frac{E_o t_o}{E_i t_i}\right)} \tag{2}$$

However, given the uncertainties, the design philosophy is mainly aimed at guaranteeing the joint's durability and creep resistance. Hart-Smith [15] suggests that the plastic zones at the ends of the joint be dimensioned to fully support the applied load, while the inner elastic zone is reserved to give the joint resistance to fatigue and creep.

Another type of approach to the problem of predicting the rupture of bonded joints consists of the application of fracture mechanic. The most well-known fracture tests are: the "Double Cantilever Beam" (DCB), mode I (**Figure 8**) [16], and the "End Notched Flexure" (ENF), mode II (**Figure 9**) [17].

The aforementioned tests allowed to obtain a failure criterion expressed as a function of the critical rates of energy release GIc and GIIc, as well as the percentage

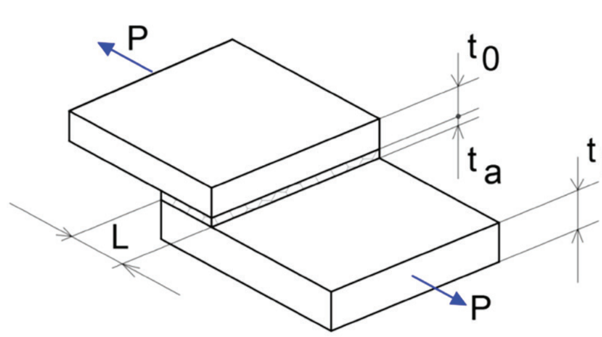

Figure 7.
Single-lap joint.

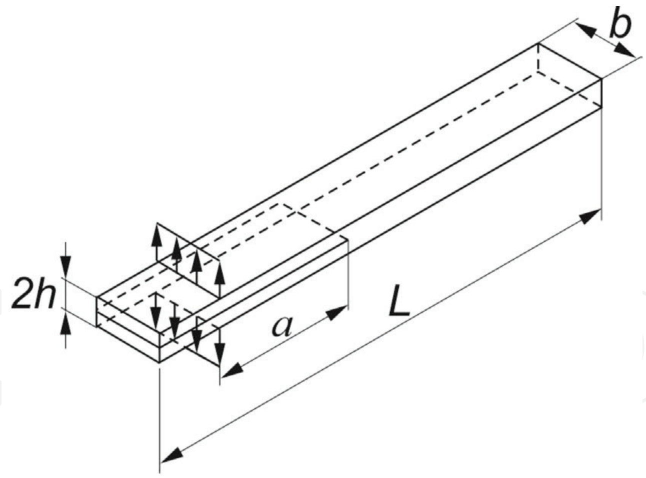

Figure 8.
DCB test [16].

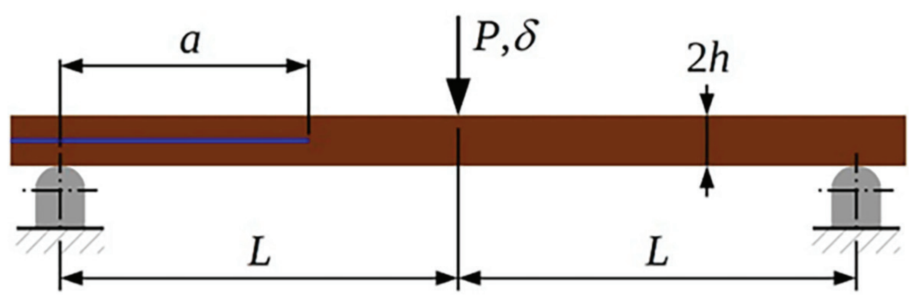

Figure 9.
ENF test [17].

of solicitation modes. This criterion was then applied to predict the failure of overlapping joints.

4. Conclusions

From the literature review carried out, it is evident that there are still many aspects to be clarified in relation to the structural performance of adhesive joints. We highlight three key issues here:

- the relevance of interfacial decohesion as a mode of rupture of adhesive joints
- the characterization of adhesives, to obtain properties that allow their selection for structural applications
- the best approach to predicting joint failure: fracture mechanics or criteria based on maximum stresses/strains.

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Conflict of interest

The authors declare no potential conflicts of interest concerning the research, authorship, and publication of this article.

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