1

Simple Practical Demonstrations

1.1 Importance of Loading Mode on Bonded Joint Performance

1.1.1 Introduction

Adhesive bonding shows many advantages over more traditional methods of joining such as bolting, brazing, and welding or even the use of mechanical fasteners. No other joining technique is so versatile, and its transversality lies in its capacity to join different materials, its ability to ensure permanent assembly, and its ease of use. In fact, a well-designed bonded joint allows for a reduction in production costs, while maintaining proper mechanical properties of the joint.

Adhesives work by exploring the adhesion phenomena, and they are usually polymeric materials, typically thermosetting, that, compared to materials that are joined in structural applications (such as metals and composites), show a much lower strength. Nonetheless, adhesive joints can be applied to a wide diversity of structures, withstanding different types of loads. To understand the mechanics of a bonded joint, it is important to first establish that the behavior of the joint is highly dependent on the type of loads it is sustaining. In an attempt to obtain the highest joint strength, it is fundamental to load the adhesive under forces acting in the plane of the adhesive layer, minimizing peeling loads. Joints are generally more resistant when shear-stressed because the adhesive layer is relatively well aligned with the loading direction. In these conditions, the entirety of the adhesive layer can positively contribute to sustain the load (see Figure 1.1). Joints subjected to cleavage or peel stresses are much weaker than those subjected to shear because the stresses are concentrated in a very small area. All the stress is located at the edge of the joint (see Figure 1.1).

1.1.2 Equipment

- One set of scissors
- Tensile testing machine

Adhesive Bonding Technology and Testing, First Edition. Ricardo João Camilo Carbas, Eduardo André Sousa Marques, Alireza Akhavan-Safar, Ana Sofia Queirós Ferreira Barbosa, and Lucas Filipe Martins da Silva.

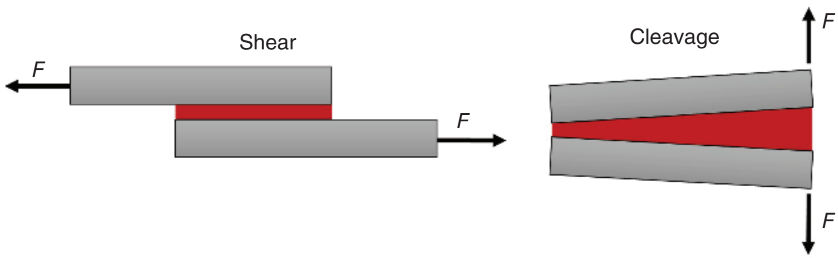

Figure 1.1 Schematic representation of the shear and cleavage loads acting on adhesive joints.

1.1.3 Materials

- One roll of double-sided foam adhesive tape
- Small aluminum beams

1.1.4 Safety Precautions

Apply the necessary safety procedures for operating a test machine.

1.1.5 Experimental Procedure

1.1.5.1 In Class

Peel the adhesive tape off the roll by applying a pulling force or “peeling” action as shown in Figure 1.2. See how easily it peels away, even if the adhesive is quite strong.

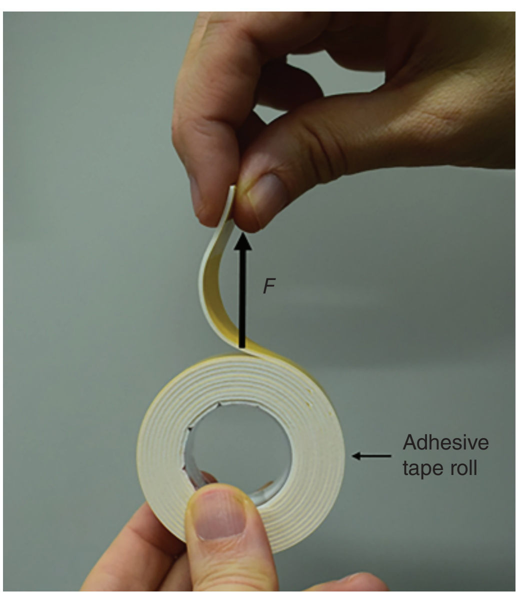

Figure 1.2 Adhesive joint under pull-out force.

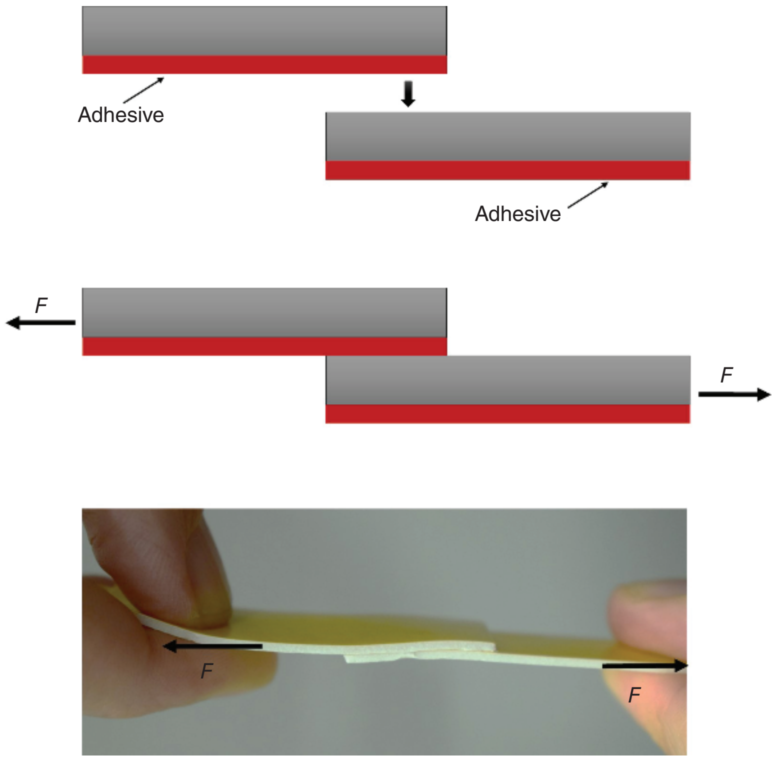

Figure 1.3 Adhesive joint subjected to shear stress, with the area being overlapped with and without the adhesive.

Now, cut two strips of adhesive tape, approximately 10 cm long. Bond the two strips parallel to each other with an overlap of approximately 3 cm. Bond the glued side of one strip to the unglued side of the other strip (see Figure 1.3). Pull on the joint in order to try to separate the strips by loading them parallelly to the adhesive layer, thereby subjecting the adhesive to shear, as schematically represented in Figure 1.3. It will be much harder to separate the joint as we are now loading it in shear; however, because of the low stiffness of the tape, it will bend and introduce some peeling loads, as shown in Figure 1.3, and this peeling can promote debonding.

Repeat the same procedure, but this time, join the strips so that the sides that have adhesive are in direct contact, as represented in Figure 1.4. When the joint is made between the glued side of both strips, it is impossible to separate the strips under shear. Ultimately, the strips will break, while the bonded area remains intact.

1.1.5.2 In the Laboratory

In order to better understand the influence of load type when an adhesive joint is used, the same tape will be bonded to an aluminum plate, and the response for two different types of load (shear and peel) will be studied using a universal tensile machine.

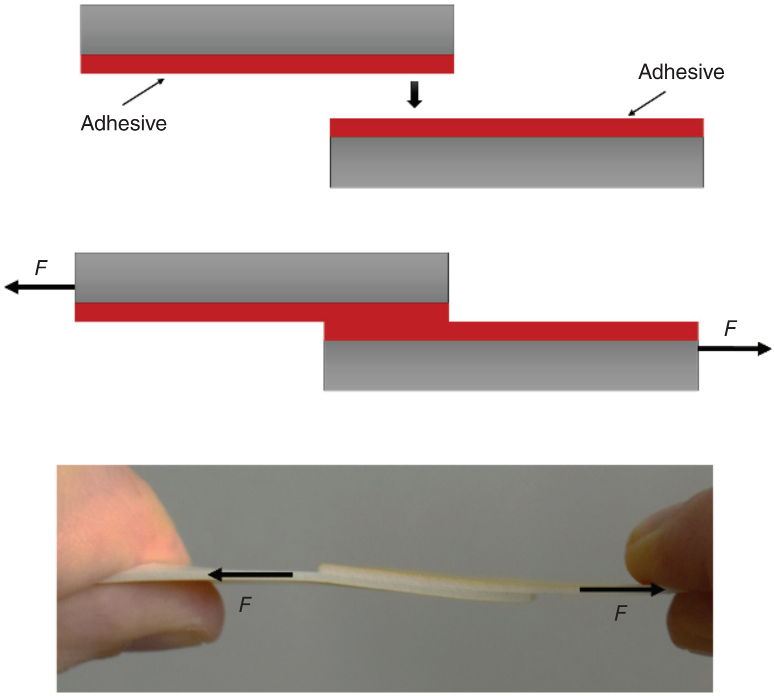

Figure 1.4 Adhesive joint subjected to shear stress, with the area being overlapped with the adhesive on both strips.

To this aim, the same tape will now be applied to metal (aluminum) adherends. Cut an adhesive tape strip, approximately 10 cm long, and join it to the surface of an aluminum adherend with a 3 cm overlap. This adhesive joint is subjected to shear stress, as shown in Figure 1.5. As the adherend is much stiffer, this adhesive joint is now subjected to an almost uniform shear stress.

The procedure will now be replicated, but this time, the forces exerted will be in a peeling direction. Therefore, it is recommended for the tape strip to be slightly longer so that it can be easily pulled off. Cut an adhesive tape strip, approximately 15 cm long, and join it to the surface of an aluminum adherend with 3 cm of overlap. This adhesive joint can now be subjected to peeling stress, as shown in Figure 1.6.

A comparison of the loads applied on the manufactured joints can be done manually or using a testing machine. Manually, it is possible to "feel" that the forces are different, but they cannot be quantified. Therefore, using a universal testing machine, the behavior of the joints loading under different types of stresses and different surface states can be easily quantified, leading to different results. Figure 1.7 shows a schematic representation of the peel and shear forces. As "felt" in a manual test, when an adhesive joint is tested in peel stress, at first, it is necessary to exert a greater force to peel off the adhesive, but over the course of the test, the force required decreases and the joint eventually fails. In turn, when the adhesive joint is being tested at shear, the force required gradually increases until failure occurs.

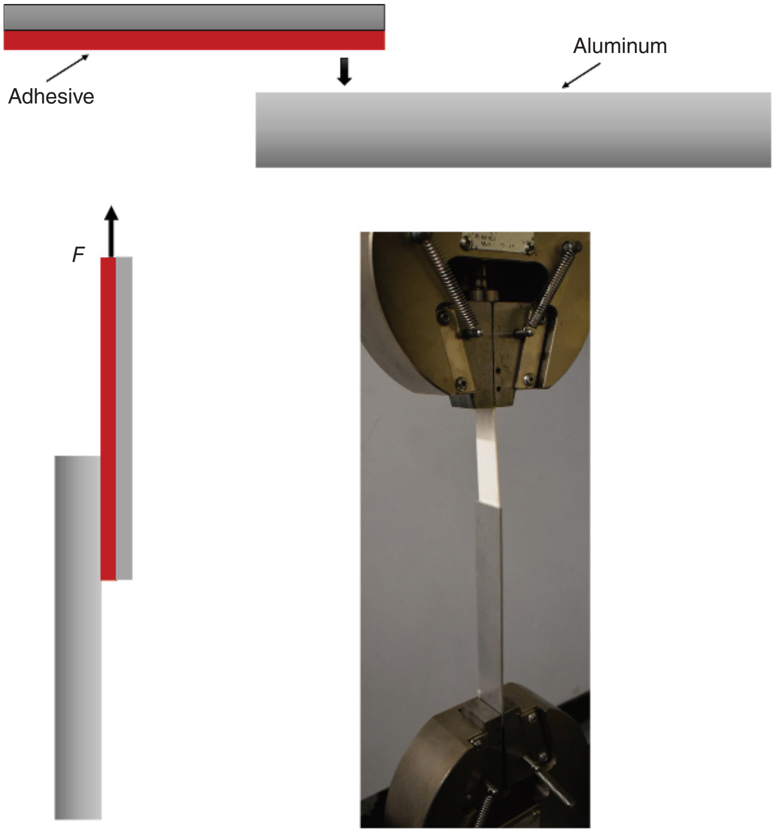

Figure 1.5 Adhesive joint using adhesive tape and aluminum adherends, subjected to shear stresses.

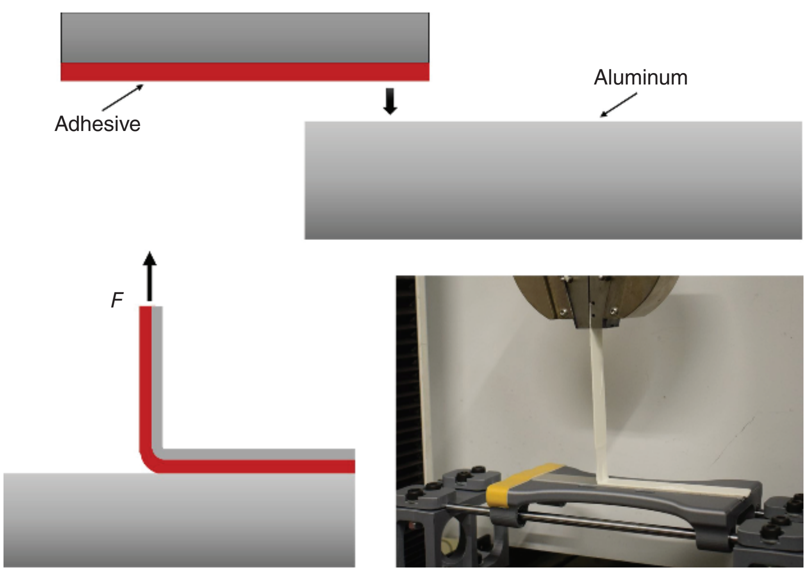

Figure 1.6 Experimental testing procedure of an adhesive joint using adhesive tape and aluminum adherends, subjected to shear stresses.

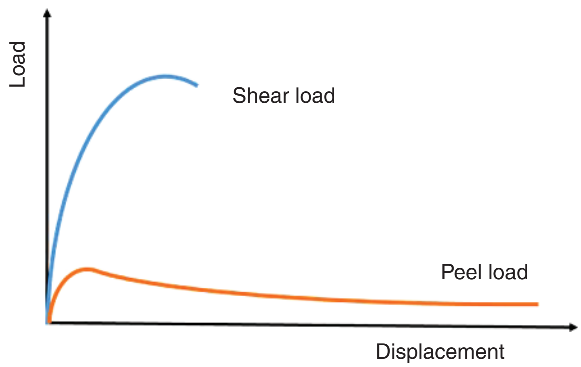

Figure 1.7 Schematic representation of the shear and peel behavior of an adhesive joint.

1.2 Surface Treatments and Methods to Evaluate Surface Energy

1.2.1 Introduction

Surface preparation of an adherend is key to achieve a strong and durable adhesive joint, and it is a process step that should never be taken lightly. The type and the quality of surface preparation will unequivocally determine the behavior of the joint. Surface treatments can be divided into two major groups: passive and active treatments. Briefly, we can explain this categorization by saying that passive treatments do not change the chemical nature of the material surface and the active processes chemically change the adherend by cleaning and removing weak layers on the surface.

How a liquid will wet a surface will mainly dictate the level of adhesion between the adhesive and the adherend. The formation of a drop of liquid on a solid surface is described by the contact angle, θ, between the solid surface and the tangent to the surface of the liquid at the point of contact as schematically presented in Figure 1.8. The aim of surface treatments is to obtain a clean and wettable surface. Unfortunately, there is no standardized procedure or equipment to assess surface cleanliness. Furthermore, a clean surface is difficult to define and sometimes even quantify. One way of evaluating the level of cleanliness is to say that a surface is clean when no dirt is visible to the naked eye. However, this is a very subjective process, and the quality of the surface treatment should always be subject to a strict control.

The value of θ can vary from zero – when there is complete liquid spreading, and we are experiencing perfect wetting – to 180° when the liquid assumes the shape of a spherical drop and does not wet the solid at all, as shown in Figure 1.9.

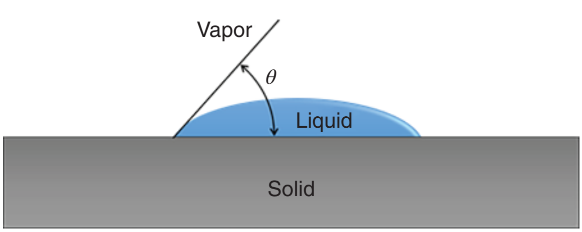

Figure 1.8 Angle of contact (θ) formed between an adherend surface and a liquid.

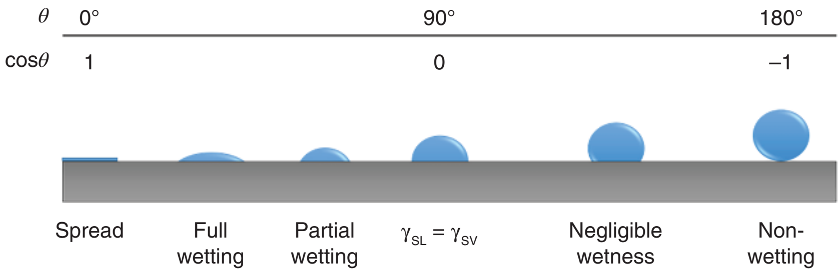

Figure 1.9 Variation of the contact angle of a drop of liquid as a function of its spreading on a surface.

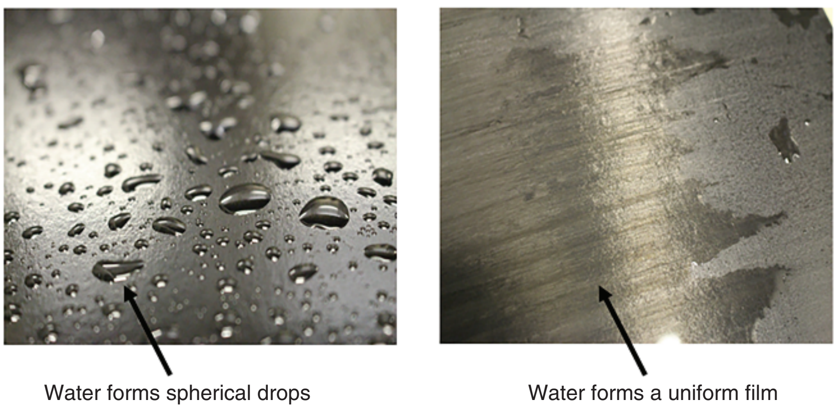

Figure 1.10 Wetting of a surface with a liquid before and after surface treatment: (a) untreated surface and (b) treated surface.

These differences can be easily observed in Figure 1.10, where the same liquid and the same surface (in this case, a composite material) behave in different ways. Before the surface treatment, the liquid does not wet the surface, forming very visible and spherical drops. On the other hand, after surface treatment, it is observed that the liquid wets the surface, forming a film. The contact angle decreases with the application of a surface treatment.

In an ideal surface preparation, the contact angle should be as close as possible to zero to ensure good adhesion. There is a wide range of surface treatments available for use with adhesive bonding processes, and consequently, the quality of the surface may vary and lead to different morphologies and surface conditions. However, the final result of a surface treatment should always be the same: an increase in joint strength and durability, achieved by promoting adhesion between the materials to be bonded and the adhesive. Regardless of the procedure used, this should always be the final goal of the surface treatment.

1.2.2 Equipment

- Plasma generator device
- Pipette
- Dyne pens

1.2.3 Materials

- Aluminum adherend (non-degreased surface)
- Aluminum adherend (surface degreased with acetone)
- Polymeric adherend (surface degreased with acetone)
- Polymeric adherend (treated with plasma)
- Water
- Acetone
- Cleaning paper (take care, as chosen paper must not contaminate the surface, not shred after the addition of the solvent, nor leave residues on the treated surface)

1.2.4 Safety Precautions

Avoid direct contact of acetone with the skin.

The plasma and anodizing treatments should be performed under an effective air extraction system because harmful volatiles can be released during the process treatment.

Surface blasting processes must be carried out in accordance with the manufacturer's safety recommendations and PPE must be provided.

1.2.5 Experimental Procedure

Surface treatment can be carried out using both passive and active methods. Depending on the class of material to be treated, a selection of the best suited methodology must be performed.

1.2.5.1 In Class

In this demonstration, a passive surface treatment method will be first used (cleaning with a solvent, acetone). This process aims to remove oily or greasy areas, which are the sources of very low wetting and adhesion. In many non-structural bonding applications, these processes are often sufficient, but they are frequently the first step of a more complex surface treatment process in structural applications.

Degreasing is the simplest method suitable to obtain a clean surface, decrease the contact angle, and increase the adhesive spreading. This procedure can be applied to a wide range of materials, such as polymers, composites, and metals. There are several methods that can be followed for the application of a solvent. In this demonstration, manual cleaning was chosen, as shown in Figure 1.11. Cleaning should always be carried out in the same direction in order to remove the dirt without re-contaminating the surface.

An active treatment procedure, as explained, will chemically alter the treated surface. It must therefore be carefully selected, taking into account the material to be treated.

There are several approaches suitable for measuring the wettability, contact angle, and consequently the surface energy of a surface. Some are simple techniques, such as observing the shape of a drop of water, while others are much more complex, such as measuring the contact angle with specialized goniometers. The use of Dyne

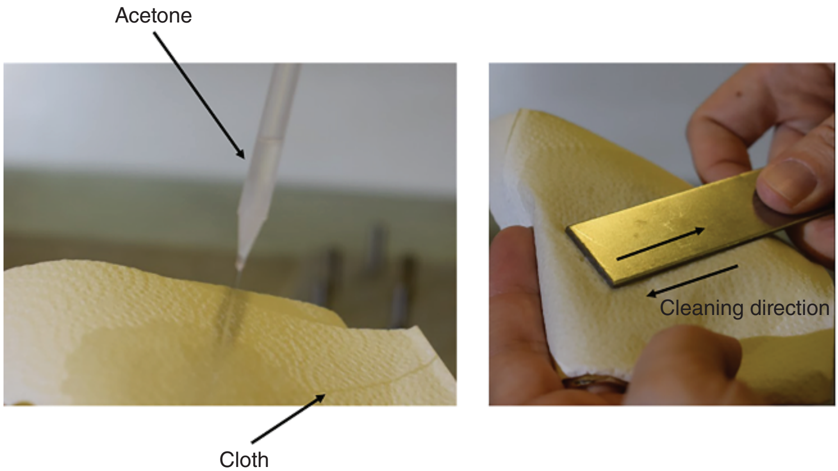

Figure 1.11 Manual cleaning of a surface using acetone and a cloth.

pens is a widely used technique for assessing the quality of surface energy. This technique is a simple, cheap, and quick method, where pens are used to draw a line of a special ink along the surface of the adherent and thus visually observe the behavior of the liquid.

To observe the shape of the drop on the treated surface, it is recommended to use a liquid whose properties are well known, and for this, distilled water is recommended. Using a pipette, a small drop is placed on the different prepared surfaces. The analysis of the drop shape will be mainly visual. If the drop has a spherical shape, this means that the liquid is not properly wetting the surface. If, on the other hand, the liquid easily spreads on the surface, this means that the treatment is facilitating the wetting of the liquid on the treated surface. It is easy to see that different surface preparations lead to different droplet shapes (Figure 1.12).

Dyne pens can also be used to quantify the quality of the surface preparation. This analysis is more rigorous than the previously described one as the use of these pens allows us to determine an approximate value of the surface energy. Dyne pens use calibrated liquids, so if the applied liquid completely wets the surface, we can then have an approximate idea of a minimum surface energy value. This test is also very effective in predicting whether the surface shows differences before and after a surface treatment. Figure 1.13 shows the application of the same calibrated liquid before and after cleaning with acetone. Before cleaning, the liquid is unable to wet the surface. After cleaning with acetone, which is a simple and non-invasive surface preparation, the calibrated liquid can already wet the surface.

1.2.5.2 In Laboratory

A plasma generator will be used to treat the surfaces of polymeric adherends. Plasma treatment is the most effective technique to increase the surface energy of polymers because it is responsible for changing the chemistry of polymeric surfaces to be treated (see Figure 1.14).

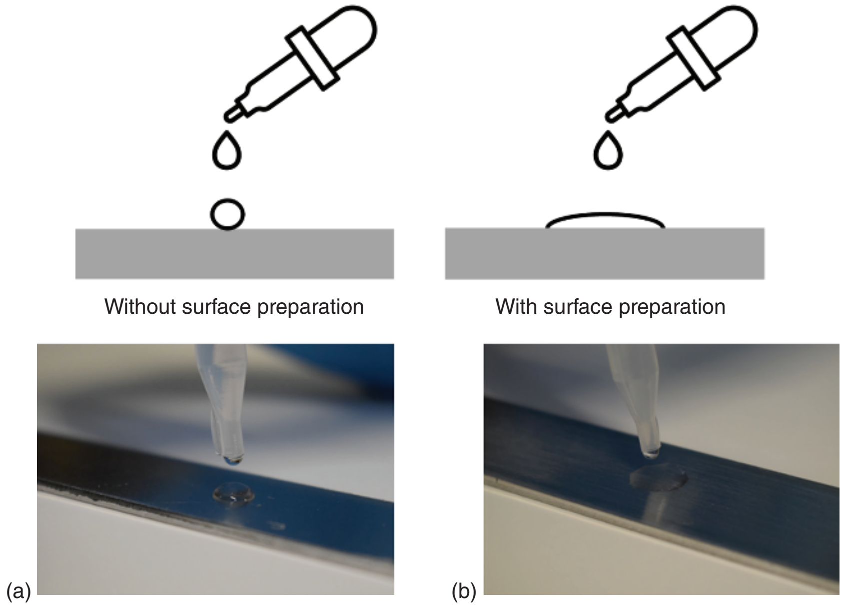

Figure 1.12 Observation of the shape of a drop of water with a liquid of known properties on metallic surface without (a) and with (b) surface treatment.

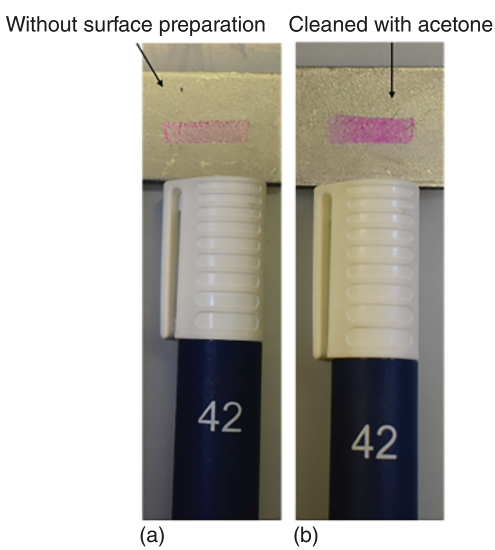

Figure 1.13 Use of Dyne pens on a metallic surface before (a) and after (b) surface preparation.

Please note that these surfaces should not be touched with hands, avoiding the introduction of grease that can contaminate the already treated surfaces. It is advisable to join the treated surfaces immediately after treatment. If this is not possible, they should be conveniently stored in a manner that ensures that there is no contamination.

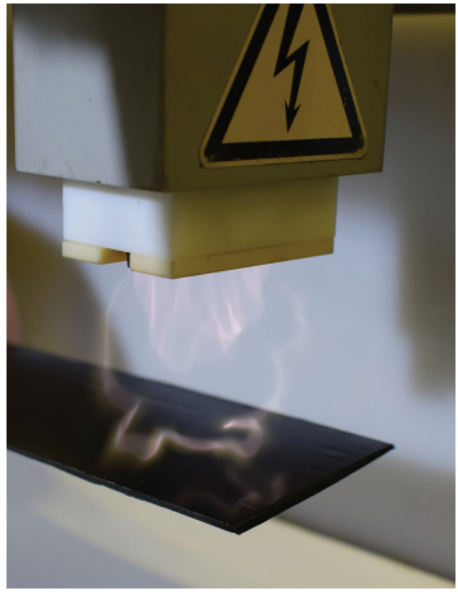

Figure 1.14 Surface of the polymeric material to be treated with plasma.

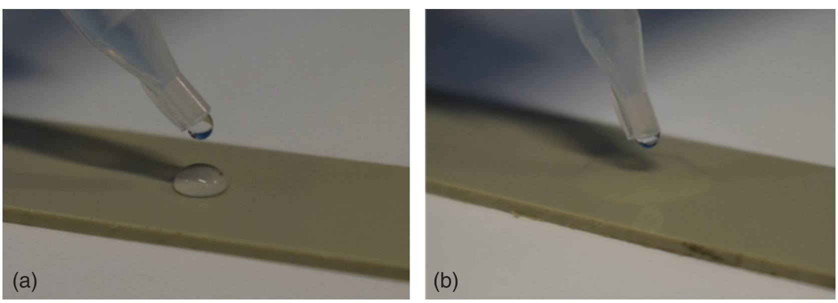

Figure 1.15 Observation of the shape of a drop of water with a liquid of known properties on a polymeric surface without (a) and with (b) surface treatment.

Figure 1.15 clearly shows that the wettability is higher when the polymer is exposed to plasma treatment, and this allows us to conclude that the adhesion is higher when the polymeric adherends are treated with plasma.

The use of Dyne pens allows us to determine the surface energy of polymeric materials; this is achieved using different pens with different calibrated liquid energies, starting with 30 up to 38 mJ/m^2. Figure 1.16 shows that the surface energy of untreated polymeric adherends is between 30 and 32 mJ/m^2 because it is clear that the liquids of this pens are able to uniformly wet the polymer.

Figure 1.16 shows that the surface energy of the polymeric adherend after treatment with plasma increases from 30 mJ/m^2 to more than 38 mJ/m^2. This means that the surfaces treated will show good adhesion with the adhesive, and after being bonded, the failure is probably cohesive.

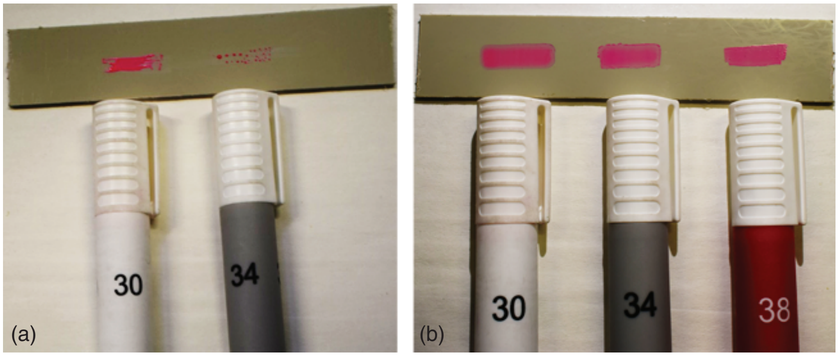

Figure 1.16 Dyne pen application on a polymeric non-treated (a) and plasma-treated (b) adherend.

1.3 Stress Distribution Along the Overlap Length

1.3.1 Introduction

Tensile loads on a single overlap joint subject the adhesive to shear and peel stresses, as shown in Figure 1.17. The shear and peel distributions in the adhesive along the overlap length exhibit a large stress gradient at the end of the overlap, where a stress concentration is present.

When considering the loads that an adhesive joint can be subjected to, shear is by far the more preferable for adhesive joints (see Figure 1.18). In this loading condition, the adhesive layer is relatively well aligned with the load direction, which means that the entire adhesive layer can contribute positively to support the load. When designing an adhesive joint, one should always try to ensure that the adherends carry the load in a manner that is as parallel to the adhesive layer as possible.

Several analytical models allow the calculation of these stress distributions, as do many numerical methods such as the use of finite element modeling, which allows us to obtain precise stress and strain distributions along the adhesive layer, providing clear information about how loaded a portion of adhesive is under service. With this demonstration, it is intended to experimentally show how the strain

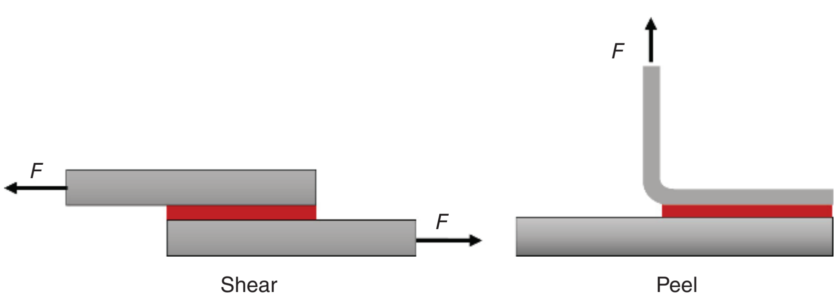

Figure 1.17 Schematic representation of adhesive joints subjected to shear and peel stresses.

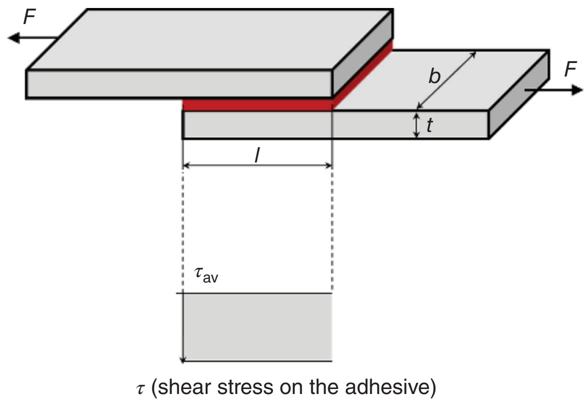

Figure 1.18 Typical bonded joint geometries for a joint under shear stress.

(and hence stress) distributions vary along the adhesive layer using a joint where the adherends are composed of hard rubber and the adhesive is simulated by a relatively soft foam rubber.

1.3.2 Equipment

- One tensile testing machine
- Black marker pen

1.3.3 Materials

- Two sheets of a hard natural rubber 25 cm × 2.5 cm × 1 cm
- One piece of foam rubber 2.5 cm × 2.5 cm
- Contact adhesive
- Acetone

1.3.4 Safety Precautions

Avoid contact with the contact adhesive and acetone.

1.3.5 Test Procedure

Clean the surfaces of the hard rubber and the foam rubber with acetone.

Join the foam rubber to the hard rubber sheets with the contact adhesive to form a single overlap joint with an overlap length of 2.5 cm.

Using the marker pen, trace vertical lines along the overlap length on the joint as indicated in Figure 1.19.

Load the joint by pulling both adherends on opposite directions and observe the deformation of the joint in the overlap length region. This demonstration can be performed in a classroom using a manually applied load. The same specimen can also be used in a tensile machine, which will allow for the stress concentrations at the ends of the overlap length to become more visible.

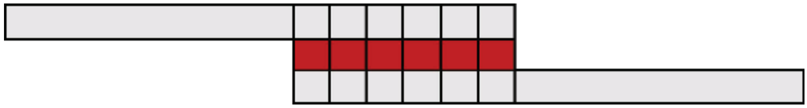

Figure 1.19 Schematic representation of the vertical trace along the length of the joint.

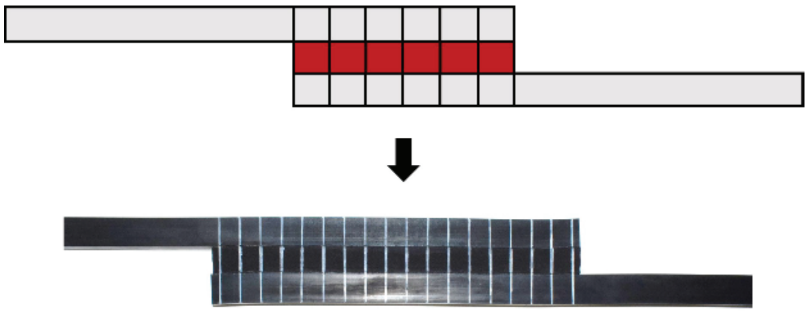

Figure 1.20 Single lap joint in an unloaded state.

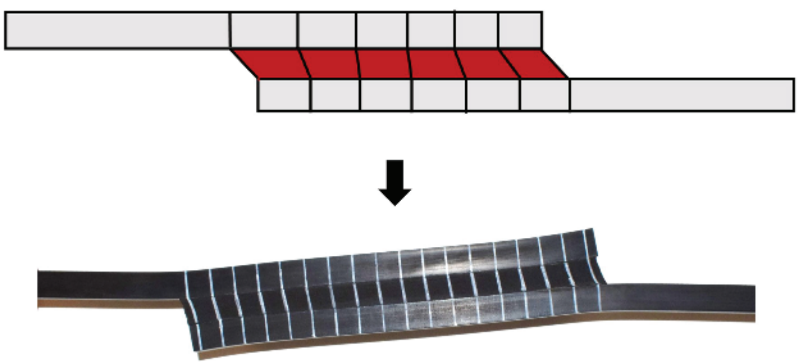

Figure 1.21 Single lap joint in a loaded state.

Observing the vertical lines made on the adhesive layer (see Figure 1.20) is a simple method to determine the level of stress present along the bondline in an adhesive joint. Figure 1.21 shows a loaded joint, and it is clear that the level of shear stress is higher at the ends of the overlap length.

Figure 1.22 schematically shows the areas of the adhesive joint where the concentration of stresses is greater, i.e. the edges of the joints.

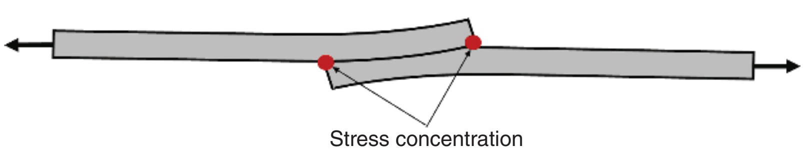

Figure 1.22 Schematic representation of stress concentration in an adhesive joint when subjected to shear stresses.

1.4 Visual Identification of Defects in Adhesive Joints

1.4.1 Introduction

Because of poor storage conditions, manufacturing problems, large internal stresses, or unexpected service loads, defects may appear in an adhesive layer or within interfacial areas. Defects should be detected whenever possible as they can significantly impact the joint strength, leading to premature failure and compromising structural integrity. Defect type, size, and location are three important factors affecting the joint strength. Porosity, cracks, voids, detachments, presence of a foreign object, poor curing, and poor adhesion are some of the defects that can be observed in a poorly manufactured joint (see Figure 1.23).

These defects can be grouped into three major groups:

- Poor adhesion (poor bonding between the adhesive and the adherend), which results from poor surface preparation or by the presence of contaminating substances in the adherend;
- Poor cohesive strength, resulting from incorrect adhesive formulation, poor mixing, or insufficient adhesive curing;
- Voids and porosities that result from the presence of air bubbles, volatile release, inadequate curing, thermal contraction, or application of the adhesive. This type of defect is most easily detectable by non-destructive techniques.

  Voids are usually created because of the presence of trapped gas/air bubbles in the adhesive mixture, even before the adhesive is applied to the surface. Voids in the adhesive layer also come from the incorrect pattern of adhesive application on the bonding surface, which can cause air to trap inside the adhesive layer. Figure 1.24 and Figure 1.25 show some of the good and bad practices associated with the application of adhesives and the manufacture of bonded joints. Following these recommendations will minimize the probability of having defects in an adhesive joint.

The presence of voids leads to a decrease in joint strength, a decrease in the adhered area, and an increase in the stress level within the adhesive layer. The presence of voids leads to a decrease in joint resistance, a decrease in the adhered area, and an increase in the stress level within the adhesive layer. Hence, a proper

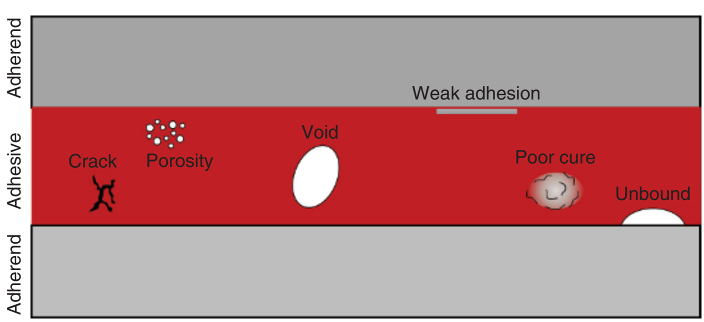

Figure 1.23 Types of defects that can be found in an adhesive joint.

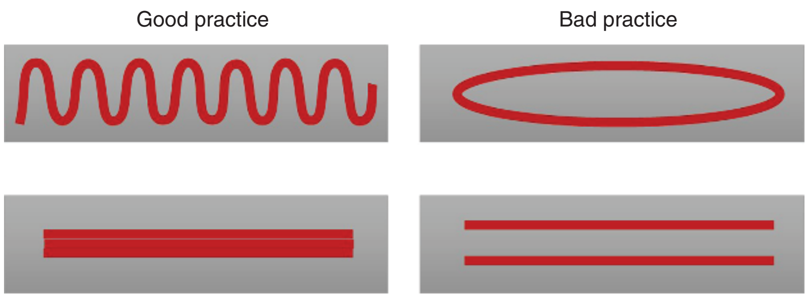

Figure 1.24 Good and bad practice in adhesive application.

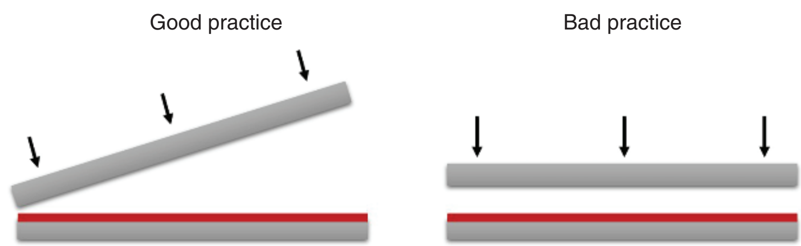

Figure 1.25 Good and bad practice in top adherend application.

quality control procedure will examine the presence of voids in adhesive layers. If air is trapped at the interface between the adhesive and the adherend, a disbonded region will be created.

Discontinuities, voids, relative sliding between adherends, insufficient amounts of adhesive, fracture, and indentations or dents are examples of defects that can be identified by macroscopic observation of the bonding area. Visual inspection as a non-destructive control method is a simple task that only allows a first identification of the bond quality.

One of the main methods used to perform the quality control of adhesive joints is visual control, not only at the time of manufacture but also after the execution of the joint. While the visual inspection method is a simple approach used to perform the quality control of adhesive joints, the inspection operator must be highly skilled and experienced. Moreover, it is crucial to provide adequate light intensity, ensure the correct viewing angle, and use the most suitable tools. The accuracy of this technique is highly dependent on the quality of the supporting installation. Visible defects and faults should be compared with reference images in inspection manuals to ensure that they are within an acceptable range.

This type of control is appropriate for identifying defects or flaws that are noticeable on the surface of the joint. In addition, geometric faults such as misalignment, non-uniform adhesive thickness, incorrectly shaped fillets, etc., can also be visually observed. Lack of excess adhesive or filleting at the edges of the bondline after manufacture may be a sign of insufficient adhesion between the adherends or a poorly secured bondline (thicker bondline).

1.4.2 Equipment

- Magnifying glass
- Metallic coin

1.4.3 Materials

- Examples of adhesive joints that are misaligned, porous, with "burnt" adhesive, with non-uniform thickness, and with missing adhesive.

1.4.4 Safety Precautions

No hazards to report.

1.4.5 Test Procedure

In Figure 1.26, it is possible to observe the geometric misalignment of an adhesive joint. It is clearly visible that the bottom adherend is not in the correct position, while the correct position of the adherend is marked in red. These joint misalignments cause stresses to be different from those expected for a given adhesive joint, which, in addition to all the dimensional errors, can lead to serious constraints in joint performance.

The correct curing process for an adhesive is always listed in the technical data sheet provided by the supplier. It is very important to follow these indications because the use of incorrect procedure (for example, too low temperature) might lead to insufficient cure, and the strength of the joint will be lower than as designed. On the other hand, if the curing temperature is higher, we can "burn" the adhesive (see Figure 1.27). In fact, both excessive temperatures and long curing times may

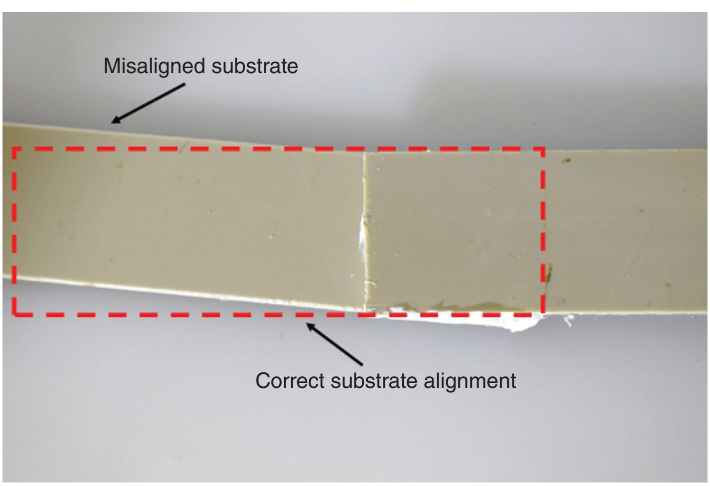

Figure 1.26 Adhesive joint with geometric misalignment of one of the adherends.

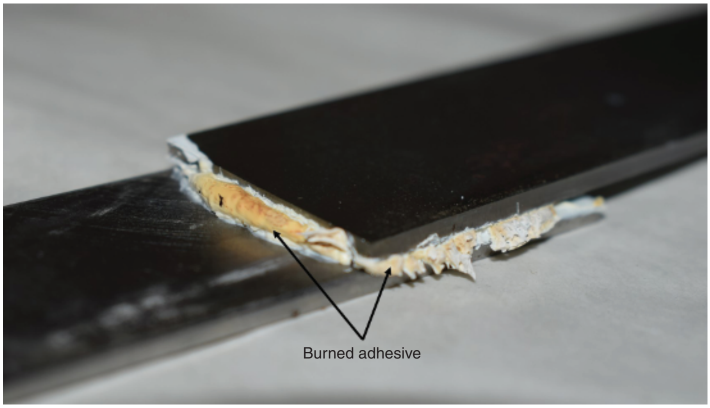

Figure 1.27 Adhesive joint showing areas of burnt adhesive due to excessive curing temperature.

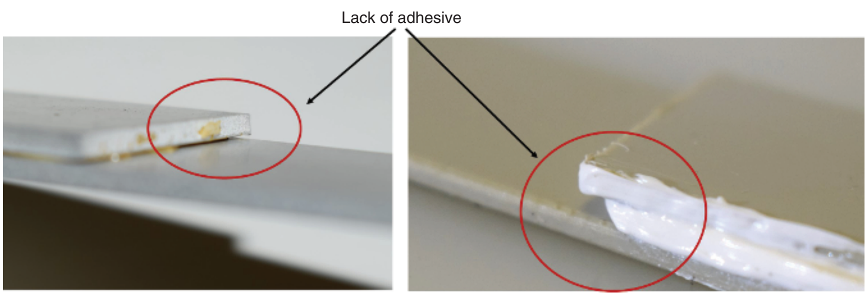

Figure 1.28 Adhesive joint missing adhesive in parts of the overlap area.

lead to a degradation of the polymeric chains, leading to a loss of chemical and mechanical properties.

One of the most common defects observed in joint production is the lack of adhesive at the edges (Figure 1.28). This defect can lead to premature failure of the adhesive joint, as only a small part of the joint is being used to attain the strength for which the joint was designed. This defect is mainly due to poor quality execution of the adhesive joint, usually by an insufficient application of adhesive or poor application of the adhesive along the length of the overlap. This defect may also be associated with an inhomogeneous variation of the adhesive layer thickness if there is no tight control of this dimension.

The tap test, like the visual test, is among the simplest NDT approaches used in practice. In this test, the joint surfaces are tapped with a tool, as presented in Figure 1.29. In our example, we will use a coin, but a hammer or even your knuckles could be used instead. An operator will listen to the reflected sound wave to determine whether the joint is qualified or not. Large unbound areas between the joint and the adhesive or the presence of significant voids will visibly alter the reflected sound. Voids or defects generate a resonant sound, whereas when there is no defect, the sound is usually hollow. While effective in detecting the existence of many defects, this approach is unable to provide information about the size or

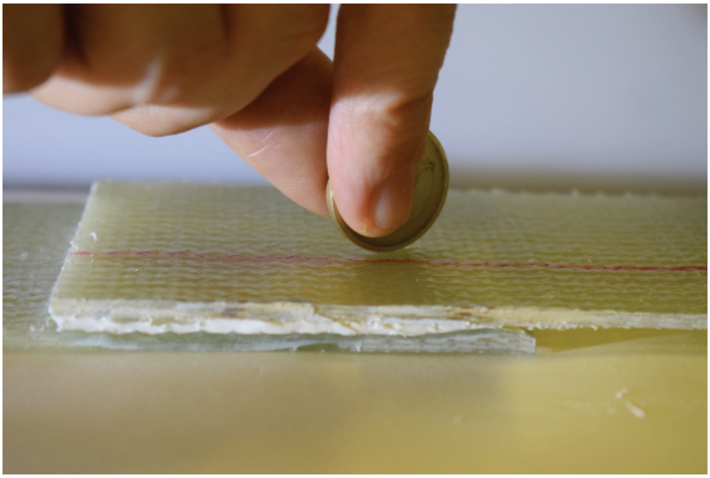

Figure 1.29 Detection of voids with the aid of a coin by the analysis of the sound emitted.

type of defects. Furthermore, if the defect is far from the surface, it will be difficult to detect using the tap test. Once again, this test is closely related to the experience of the operator.

1.5 Failure Analysis of Adhesive Joints

1.5.1 Introduction

The ultimate purpose of an adhesive joint is load transfer between the two bonded components, maintaining its structural integrity under static and/or dynamic stresses and adverse environmental conditions (temperature and humidity). It therefore becomes fundamental to correctly assess the distribution of the stress profile and, consequently, the failure modes induced in the bonded joints.

In the majority of failures in adhesive joints, it is possible to distinguish three different failure modes (Figure 1.30):

- cohesive breakage inside the adhesive,
- adhesive breakage at the interface between the adherend and the adhesive, and
- breakage of one of the adherends.

These three failure modes are schematically presented in Figure 1.30.

Adhesive failure occurs when there is poor surface preparation. This happens when there is a loss of adhesion between the adhesive and the adherend. The bond (chemical and mechanical) that should solidly connect the adhesive to the adherent is somehow lost and there is a clear separation between these two materials at the interface. When we have adhesive failure, it is possible to accurately determine the strength of the adhesive layer using a variety of models that are based on the mechanical properties of adhesive materials. The same is not true when we have adhesive failure, as the interface properties are extremely difficult to determine and may depend on several complex factors.

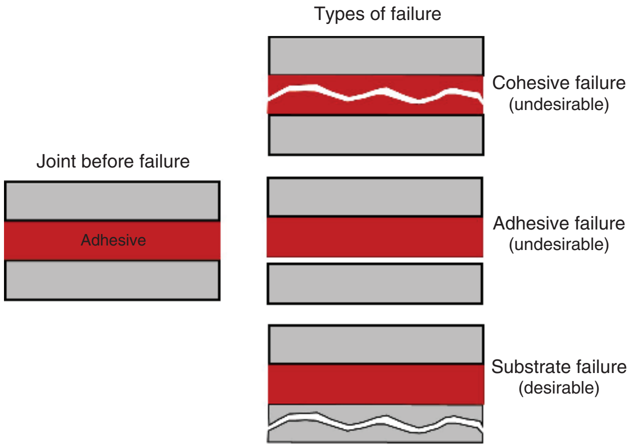

Figure 1.30 Schematic representation of the different failure modes in single overlap bonded joints.

On the other hand, a joint must be designed so that the weakest element is the adherend, i.e. failure never occurs through the adhesive. When this type of failure occurs, it is known that the adhesive joint is designed to be stronger than the material being joined. When failure occurs in the adherend, this does not necessarily mean that the adherent will break cleanly, and the adhesive layer will remain intact. Often, the adherent will instead yield and become permanently deformed (in the case of metals) or delaminate (in the case of composites), and this can then lead to the failure of the adhesive layer. Ultimately, a correctly designed and produced joint will be one in which adherend failure occurs first, even if the adhesive itself becomes damaged and fails as a result of this.

When an adhesive joint is manufactured using composite laminates, the situation may be more complex, so it is advisable to use adherends that have surface layers with fibers oriented parallel to the direction of stress, seeking to avoid interlaminar failure of these layers.

1.5.2 Equipment

- Magnifying glass
- Protective gloves

1.5.3 Materials

- Fractured adhesive joints, showing adhesive, cohesive, and interfacial failures
- Adhesive joints with metallic and polymeric adherends (with and without deformation)
- Composite adhesive joints

1.5.4 Safety Precautions

Gloves should be worn to avoid skin injuries caused by the sharp fibers that are presented in the fracture composite materials.

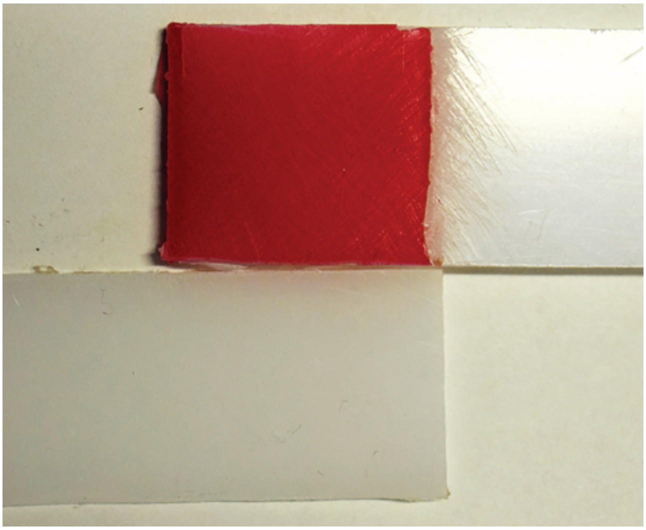

Figure 1.31 Adhesive joint with adhesive failure.

1.5.5 Test Procedure

This work consists in the careful observation of the fracture surfaces of different adhesive joints. Ideally, the observation can be done with the naked eye, but in more complex cases, more sophisticated equipment should be used, such as magnifying glass or a microscope (optical or electron).

In Figure 1.31, an adhesive failure is observed, whereupon the adhesive does not bond to one of the adherends, and the failure occurs at the interface between the adhesive and the adherend. As already described, this type of failure is highly undesirable. This sort of failure means that the surface preparation is not ideal, leading to a premature failure of the adhesive joint.

A cohesive failure in the adhesive is demonstrated in Figure 1.32. Failure occurs in the middle of the adhesive layer, demonstrating good adhesion of the adhesive to the adherends. Although better than adhesive failure, this type of failure is also undesirable in practical applications as the adhesive is still the weakest link within the joint.

The adhesive joint shown in Figure 1.33 shows adherend failure. In other words, it can be concluded that the joint is well designed, and the surface preparation is well executed as the weakest element of the adhesive joint is now the adherend material and not the adhesive layer or its interface. In this specific case, it is easily seen that there is a great concentration of stresses at the edge of the adhesive joint overlap coupled with massive plastic yielding of the polymeric adherend.

The same adhesive can be used to manufacture adhesive joints with metallic adherends using hard steel. In this case, failure occurs within the adhesive, and, unlike the joints bonding the polymeric material, there is no yielding of the metallic adherends. However, some voids can still be noticed, suggesting that the adhesive mixture or applications was not perfect. In this case, the surface preparation is also

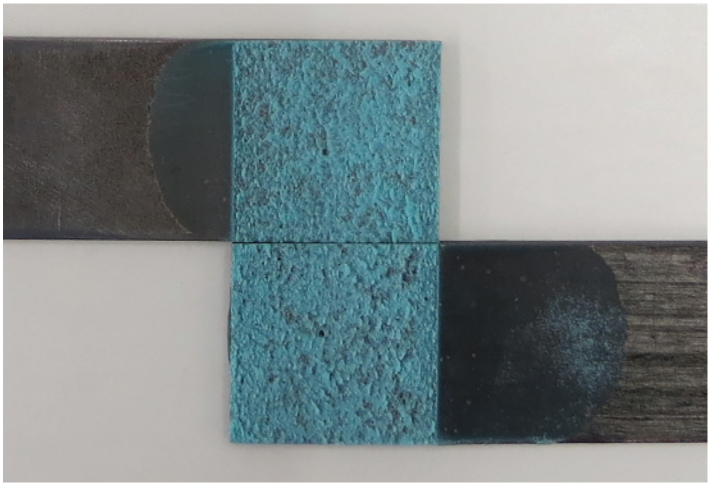

Figure 1.32 Adhesive joint with cohesive failure in the adhesive.

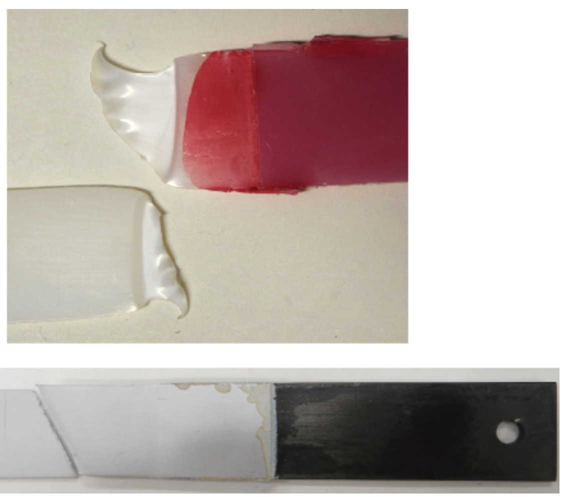

Figure 1.33 Adhesive joint with adherend failure.

appropriate because there is adhesion between the adhesive layer and the adherend (Figure 1.34).

In Figure 1.35, showing a mixed failure, it is visible that the failure mechanism is half cohesive and half adhesive. Occurrence of adhesive failure means that the surface treatment can be improved in order to improve the adhesion, obtaining cohesive failure.

In Figure 1.36, it is visible that adherend delamination occurs, as composite fibers separate from the matrix material and become exposed. This type of failure is very disadvantageous because it occurs in the areas where the peel stresses generated

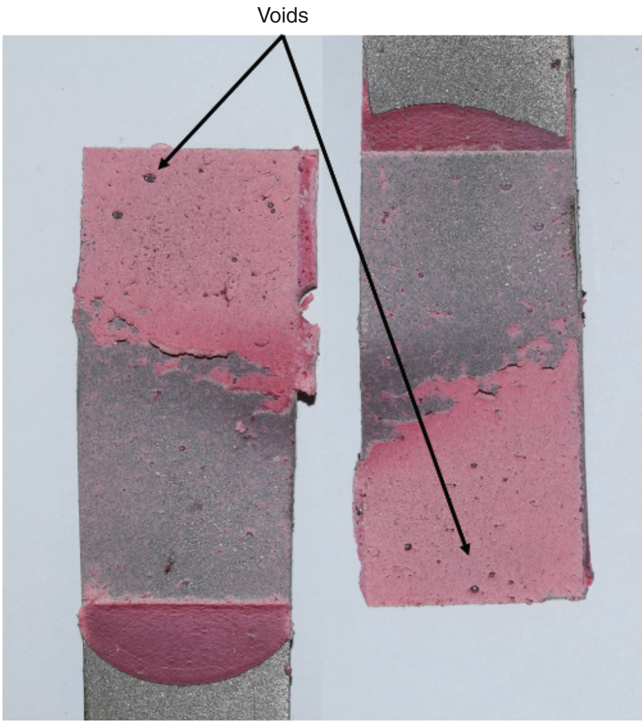

Figure 1.34 Cohesive failure in the adhesive layer, in metallic adhesive joints.

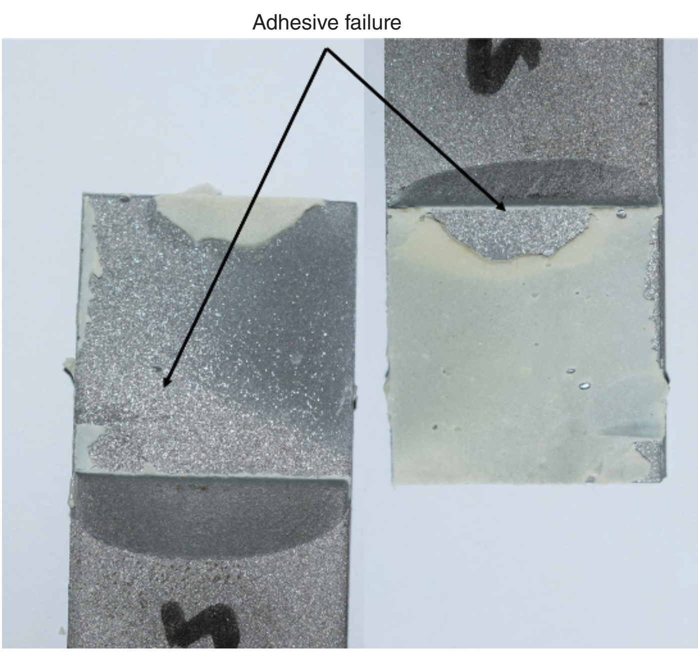

Figure 1.35 Mixed failure (cohesive and adhesive failure).

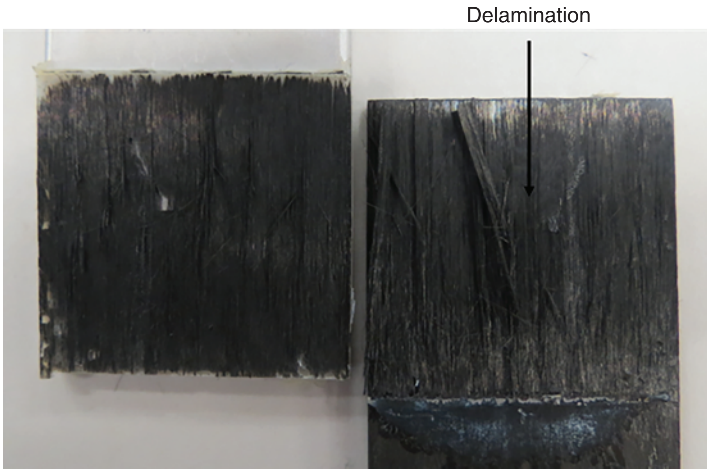

Figure 1.36 Example of delamination failure of composite joints.

by the adhesive layer are at the highest and the poor transverse strength of the composite is overcome. In these cases, it is necessary to redesign the joint in order to ensure that there is no delamination. This can be done, for example, by reinforcing the overlapping area with fillets or chamfers.