STRUCTURAL ADHESIVE BONDING IN AEROSPACE APPLICATIONS

EDUARDO A. S. MARQUES
RICARDO J. C. CARBAS
ALIREZA AKHAVAN-SAFAR
A. FRANCISCO G. TENREIRO
LUCAS F. M. DA SILVA

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AUTHORS
Eduardo A. S. Marques · Ricardo J. C. Carbas · Alireza Akhavan-Safar · A. Francisco G. Tenreiro · Lucas F. M. da Silva

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The aerodynamical qualities of bonded fuselages are also superior to those obtained with riveting, since the outer surfaces of the joints are much smoother and completely devoid of discontinuities resulting from the presence of rivets, fasteners or welding beads. Although the use of flush rivets can in part compensate for this difference, these come with a much higher process cost.

1.3.2. Limitations

Some important limitations are associated to the use of adhesive joints. One of the most important is certainly the indispensable requirement for a careful and appropriate surface treatment preparation, especially for bonding polymeric and composite substrates. As we will see in Chapter 2 and Chapter 3, an incorrect surface preparation can have a major effect on joint strength and cause premature failure of the joint.

Another important limitation of adhesive bonding is related to its sensitivity to the loading direction. Adhesive joining performs very well for shear loads but exhibits low resistance to peel and cleavage stresses. These loading modes are shown schematically in Figure 1.8.

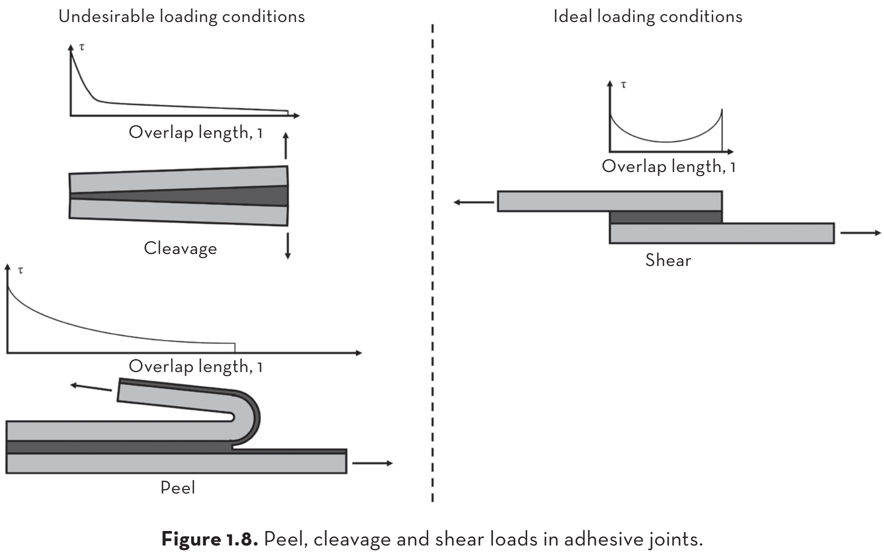

Figure 1.8. Peel, cleavage and shear loads in adhesive joints.

Cleavage occurs when the load is concentrated on one end of the joint, while the opposite side remains effectively unstressed. In essence, this type of load pries the joint open, almost as if a lever was applied at the end of the adhesive layer. Consequently, the stresses acting on the adhesive are maximum near the area where the cleavage load is being applied and minimum at the opposite end of the joint. It is this concentration of stresses that results in a very low resistance to cleavage.

and consequently improve performance and fuel consumption. This type of composite heavy construction relies greatly on adhesive bonding, dispensing fatigue prone fastening and riveting whenever possible.

The bonded components present in a helicopter are varied and include, for example, the main and tail rotor blades, cabin floors and doors, fairings and aerodynamic stabilizers. Since many of these components present quite flat bonding surfaces, film adhesives are extensively used, providing good design tolerances and easing the manufacturing process (Figure 1.12).

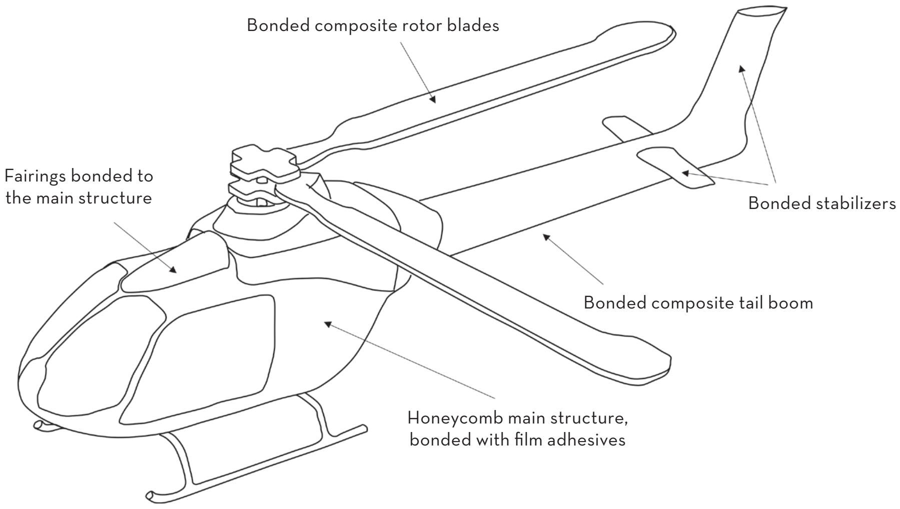

Figure 1.12. Main areas of adhesive use in a modern helicopter.

1.4.2. Space applications

The space sector makes extensive use of adhesive bonding in the construction of launch vehicles and satellites. As is the case for many other sectors, the use of adhesive bonding in these applications is strongly intertwined with that of composite materials. While at the beginning of the space race both launchers and satellites were mainly made of metal, composite monolithic structural parts started to become the norm in the 1970s, replacing many (but not all) metallic structures. This use was due to the association of epoxy resin with glass and boron fibres, which led to improved strength and stability to composite, although its use was with still limited to secondary structures such as fairings and supports. In the 1980s, the use of carbon fibre started to become the norm and opened the use of composites in primary structural parts, in monolithic structures or sandwich panels. Nowadays, many rockets include fully adhesively bonded composite stages which serve as tanks, holding propellant cooled to cryogenic temperatures. Some of these applications are shown in Figure 1.13.

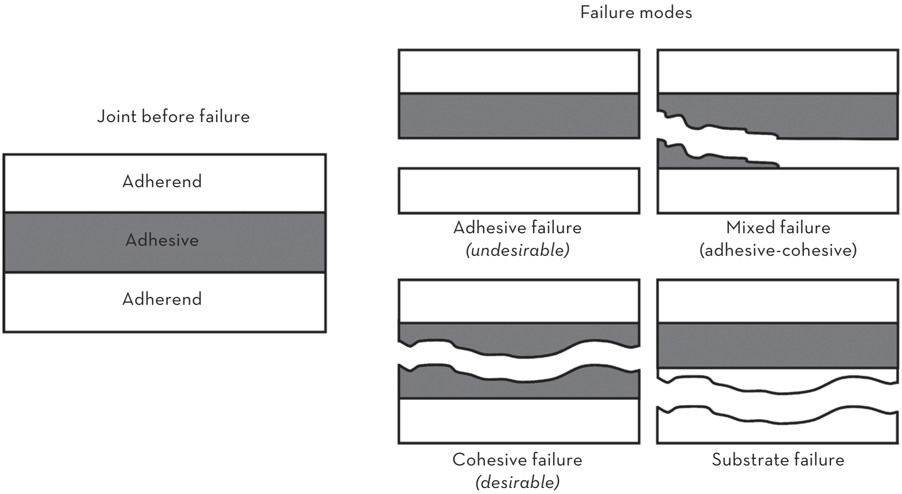

Figure 2.1. Typical failure modes in bonded joints.

It is at the interface that adhesives bond to adherends, forming chemical bonds. The forces involved depend on the chemical nature of the surfaces of the materials in question. The bonds that can be formed are divided into primary and secondary bonds, as seen in Figure 2.2.

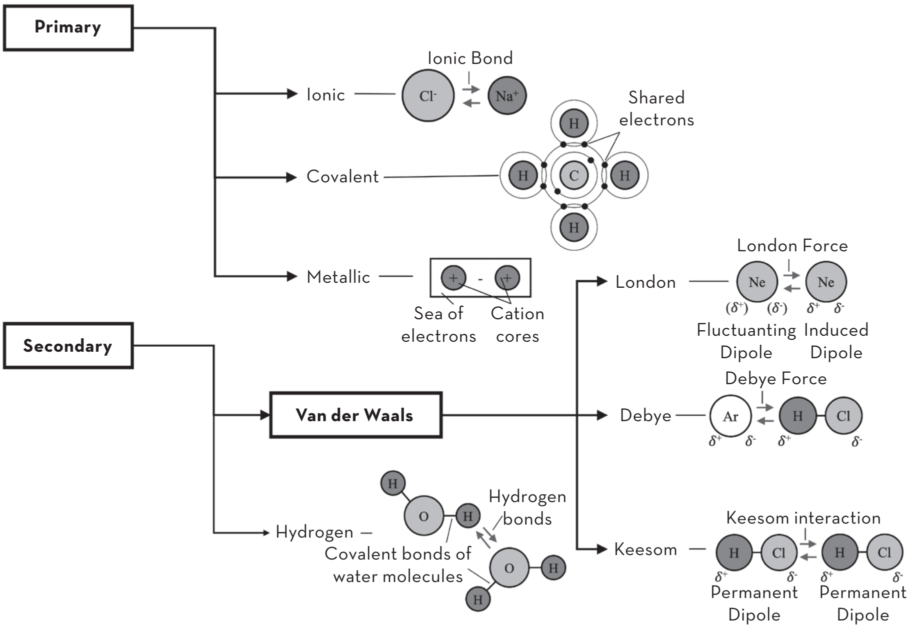

Figure 2.2. Types of bonding forces acting in adhesive joining.

In a liquid, as is the case for an uncured adhesive, the forces of attraction between the molecules are in a condition of equilibrium in all directions. On the surface of the liquid this kind of equilibrium cannot exist because there are no neighbouring molecules outside the surface. These molecules are subjected only to a force which pulls them into the liquid (see Figure 2.7). To bring new molecules to the surface, additional work must be done and thus the molecules at the surface must have a higher energy than those on inside the liquid. This extra energy of the molecules at the surface is called surface free energy or simply surface energy, expressed as energy per unit area (with units $mJ\ m^{-2}$). More precisely, this corresponds to the energy required to create one unit area on a surface.

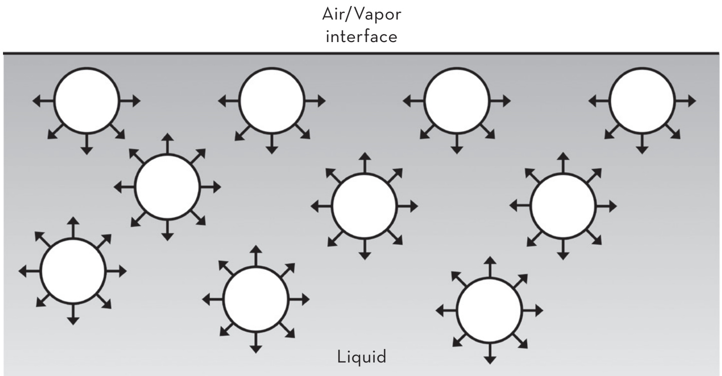

Figure 2.7. Air/liquid equilibrium at the surface of a fluid.

The minimum energy principle is used to determine whether or not a liquid spreads on a solid surface. This principle explains why a liquid spreads on a solid with a higher surface energy but not on one with low surface energy. If the high energy solid surface is replaced by a lower energy surface (the liquid), then the total energy of the system is reduced and this will be a spontaneous process.

To summarize, it can be stated that:

- Energy of the liquid (γ_L) < Energy of the solid (γ_S) the liquid spreads
- Energy of the liquid (γ_L) < Energy of the solid (γ_S) the liquid does not spread

High energy surfaces are those where γ_S varies between 500 and 5000 $mJ\ m^{-2}$, corresponding, for example, to metals and their oxides, relatively hard materials with high melting points. Low energy surfaces, on the other hand, have a γ_S between 5 and 100 $mJ\ m^{-2}$; these include most polymeric (and composite) materials.

3.2.1.2. Abrasive processes

Abrasive surface treatments can be carried out manually or assisted with powered equipment and machinery. These are widely used to prepare the surface of a substrate, representing an inexpensive and practical methodology that does not require highly specific equipment.

Manual abrasion processes, using sandpaper, brushes and metal wool, depend largely on the experience of the operator. If performed incorrectly, they provide inconsistent results and should only be used if no other method is possible. Furthermore, when a dry abrasion process is employed, it is strongly recommended to include an initial degreasing step in the full procedure, preventing surface residues from becoming embedded in the surface to be treated or being transferred to other areas of the surface by the sandpaper, reducing the effectiveness of the process.

Since surface abrasion results in well oriented grooves, it should always be carried out in alternating, crosswise (perpendicular to each other) movements to ensure that there is no preferential direction of treatment on the surface. On completion of the process, particles and dust should be thoroughly cleaned from the surface, which can be achieved using an oil-free blast of compressed air, or by repeating a cleaning process using a solvent or a degreasing agent.

Gritblasting or sandblasting is a widely used surface preparation for metal substrates. In this method, compressed air is used to propel abrasive particles against the surface to be treated, allowing rapid removal of contaminants and oxide layers. This method requires an investment in equipment, although the cost of suitable equipment is not very high due to its relatively simple construction, as shown in Figure 3.4. It should be noted that each type of material requires a specific procedure, using different shapes, particle sizes and operating pressures.

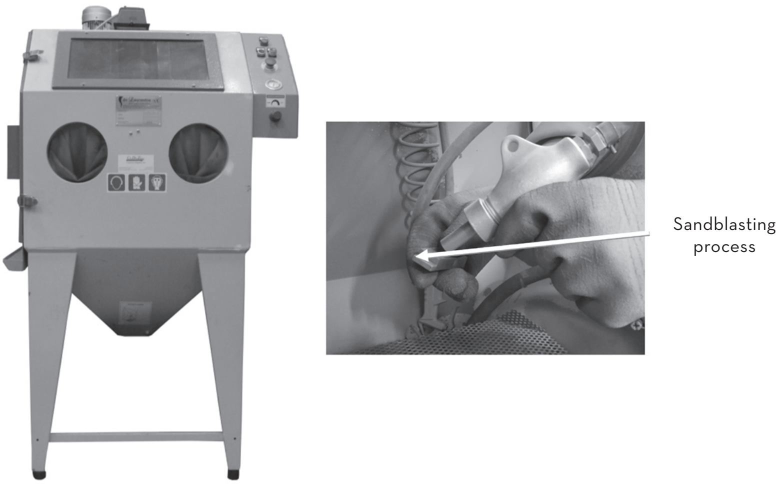

Figure 3.4. Sandblasting process of metallic substrates.

4.1.4. Comparison between the performance of different structural adhesives used in aeronautical construction

Figure 4.5 shows a comparative analysis of the strength and the service temperature of different structural adhesives used in aeronautical construction. This comparison clearly shows that phenolic adhesives are generally weaker than epoxy and aromatic adhesives and can be used up to 200 °C. One component epoxies are the strongest of these group, possessing extraordinary strength at room temperature. However, their performance drops quickly as the temperature rises. Finally, the aromatic adhesives can retain their strength at very high temperature, offering unrivalled performance under these extreme conditions.

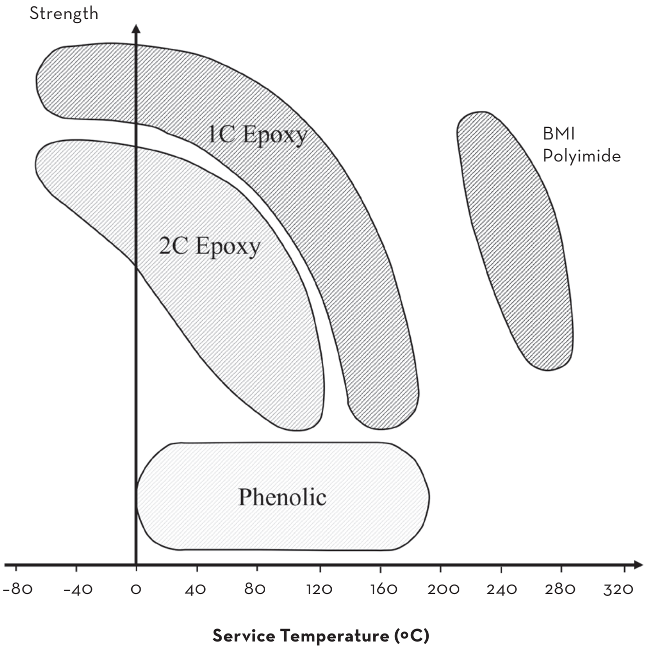

Figure 4.5. Comparison of the strength and service temperature of different adhesives used in the aeronautical industry.

4.2. NON-STRUCTURAL ADHESIVES AND SEALANTS

4.2.1. Elastomeric adhesives

Elastomeric adhesives (Figure 4.6) are very flexible materials and can be based on natural or synthetic rubber-based materials. These adhesives do have excellent peel strength and toughness but exhibit low shear strength, which makes them unsuitable for most structural bonding applications. Still, their extreme elasticity and toughness results in good fatigue and

5.6. ADHESIVE HARDENING

The process of hardening adhesives is highly dependent on the nature of the selected adhesive. Adhesives which harden with temperature can be subjected to stages in oven, autoclaves or even in hot-plate hydraulic presses. Autoclaves, large pressurized and heated chambers, are especially important in the aerospace sector. Autoclaves typically can reach temperatures over 240°C within 45 minutes and do so with a good accuracy (less than 0.9°C of temperature variation inside the chamber). They can also be pressurized up to 10 bar, further supplemented by the use of vacuum bags (Figure 5.6). In modern aerospace manufacture, the use of autoclaves is essential to produce defect-free composites and bonded joints.

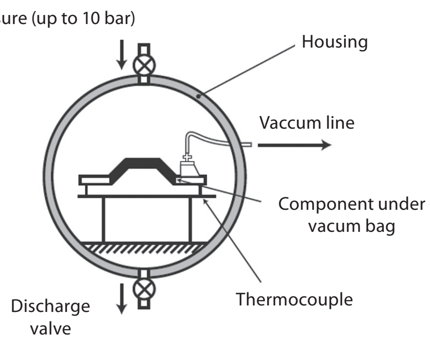

Figure 5.6. Scheme of an autoclave used to manufacture components of bonded and composite construction.

The process time, temperature and the pressure are the most important parameters that should be controlled during the hardening process. Besides the exposure to heat, other sources of energy, such as radiation, and moisture can also be used to harden adhesives, requiring specific equipment such as ultraviolet lamp lights or radiation sources. In two-part adhesives, the hardening process does not necessarily require exposing the adhesive to heat, although higher temperature can generally be used to accelerate the process. Regarding form, paste adhesives generally have a lower curing temperature than film adhesives, which is advantageous for bonding substrates of dissimilar coefficients of expansion.

A well-known technique employed for localized hardening in the aeronautical sector is the use of heated blankets. As shown in Figure 5.7, a blanket containing resistors is heated up by passing an electrical power through it. The supplied electrical power is controlled to provide sufficient heat for local hardening of the structure or of the repair patch. These blankets are made to be quite flexible which makes them suitable for operating on curved structures such as those found in airframes.

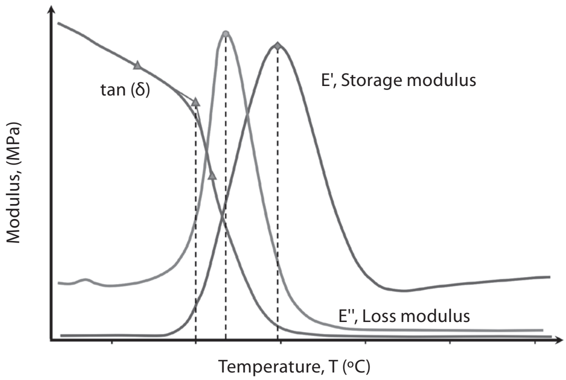

Figure 6.2. Determination of the glass transition temperature of an adhesive by identifying the temperature at which a peak in damping occurs (DMA analysis).

6.1.2. Surface state

Wettability (or surface energy) is another critical factor in qualified bonded joints. As we have seen in Chapter 3, the lower the wettability, the higher the risk of the interfacial failure and the lower the joint strength will be, especially when adhesive joints are used for repair purposes. This reduction in adhesion can be caused by contamination due to the presence of fluids (hydraulic fluids or fuel for example) or other types of contamination. Dyne pens are very simple tools that can be used to quickly analyse the surface energy of the adherends. Using a specific marker, a line is drawn on the adherend surface and a breakage of the lines into smaller sections shows that the surface energy is lower than what has been specified by the grade of the used marker. Directly measuring the contact angle of the adhesive is another way to ensure an adequate surface energy of the adherends. The higher the contact angle, the lower the surface energy and consequently the lower the adhesion quality will be (see Figure 6.3).

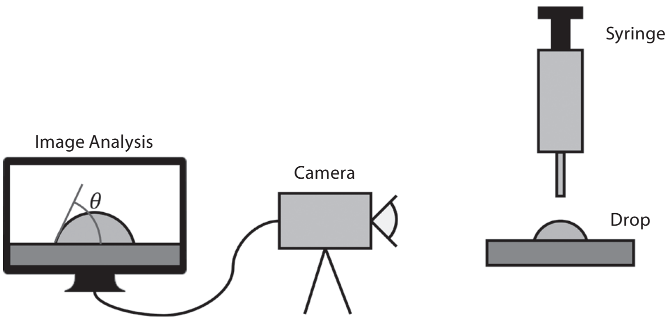

Figure 6.3. A schematic representation of the equipment used for measuring the contact angle of a drop on an adherend surface.

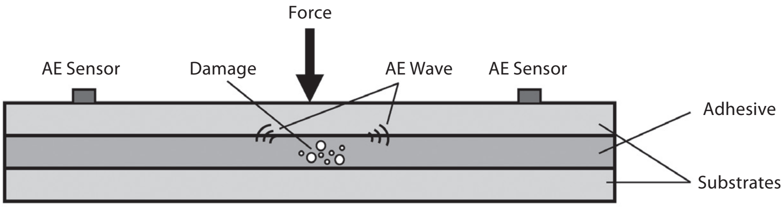

Figure 6.14. Schematic representation of the acoustic emission method and its operation principle.

Some authors consider this technique as a destructive test, given that the specimen needs to be mechanically loaded to generate the necessary waves and vibrations, although the monitored structure is still expected to be fit for service after the test is completed. In fact, just the act of generating an excitation signal with a small load or impact has the potential to induce damage (however minor) in the structure.

6.3.3.7. Lamb wave method

Lamb waves are a type of ultrasonic elastic wave that propagates through a bounded medium such as a bonded structure, generating multi-modal and dispersive waves. Given their complexity, these waves can be subdivided into symmetric quasi-axial waves, or S- waves, and antisymmetric quasi-flexural waves, or A-waves. These exist simultaneously, making their propagation extremely complex in nature and difficult to process. In Lamb wave-based NDTs, a signal generator generates a transient electric signal that is sent to a piezoelectric actuator, which in turn converts the signal into ultrasonic Lamb waves. When the generated waves reach a given defect, these are partially reflected and partially transmitted, similarly to what occurs in traditional ultrasonic waves. Piezoelectric sensors convert the received waves into an electric signal which is then read by a data acquisition system and a computer for signal processing (Figure 6.15).

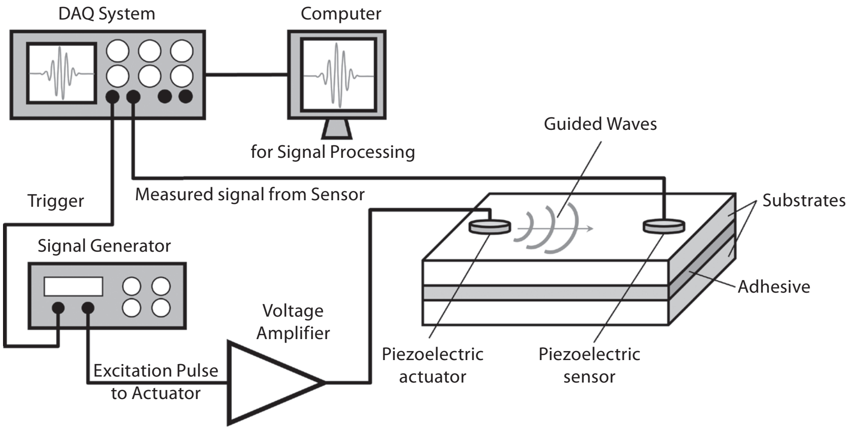

Figure 6.15. Schematic representation of the lamb wave method and its operation principle.

In case of all-composite fuselages or components, the issue of thermally induced stresses in repair patches is much lower. However, in this case the repairs are much more complex in nature, since the damage mechanism are usually complex (for example, the laminate splitting due to impact loads and hole damage shown in Figure 7.6) and the repair techniques must consider the layered construction of the composite adherends and repair this layup accordingly.

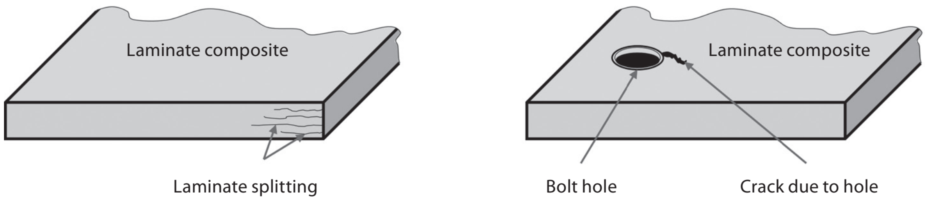

Figure 7.6. Examples of types of damage generated in composite structures.

In the case of simple laminate panels, repairs are usually performed with the assistance of a film adhesive. The damaged area is first bored out and cleaned and the filler plies of a prepreg composite are inserted in the void, supported by a backup ply. Alternatively, a tapered hole is created, which is filled with successive layers of repair plies, topped by a final, extra ply. Vacuum bags and heated blankets can then be applied over these repairs in order to harden both the film adhesive and the prepreg composite plies These methodologies are shown schematically in Figure 7.7.

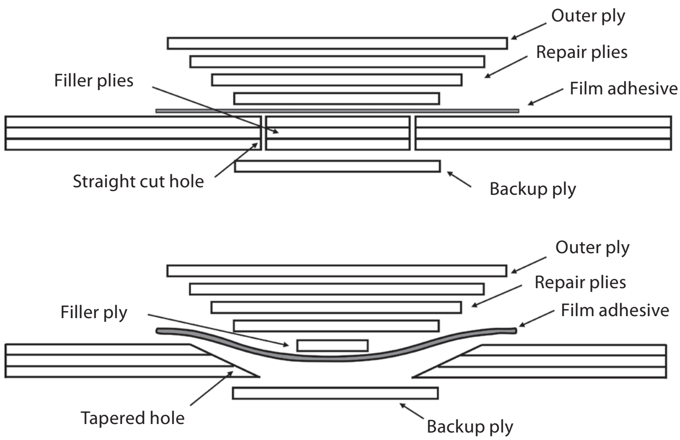

Figure 7.7. Repair process of a laminate panel.

Should the structure to be repaired consist of a composite honeycomb panel, the repair procedure is slightly different. These processes usually start with the insertion of a new section of replacement core in the honeycomb, which is bonded into place using a core features have greatly expanded, including more advanced capabilities to model adhesives and adhesive joints.

The FEM first divides a structure into a mesh of small elements, connected by multiple nodes. Boundary conditions are applied to this mesh, mimicking the loads acting on the real component. A system of equations is then established combining the influence of each node and element and their boundary conditions. The goal of the FEM is to determine the displacement of the nodes (D), having prior knowledge of the stiffness of the body (K) and the loads and reactions acting on it (R). Thus, based on the mechanics of elasticity, an equation can be established which states that the K.D=R. Generally speaking, FEM is known for its capability to adapt to any kind of geometry and its flexibility in the calculation of stress values and fields. However, due to the time necessary to create, modify and calculate a model, it is less practical for quick parametric studies than the previously discussed analytical models. An example of a simple model of a bonded T-joint created with FEM is shown in Figure 8.11.

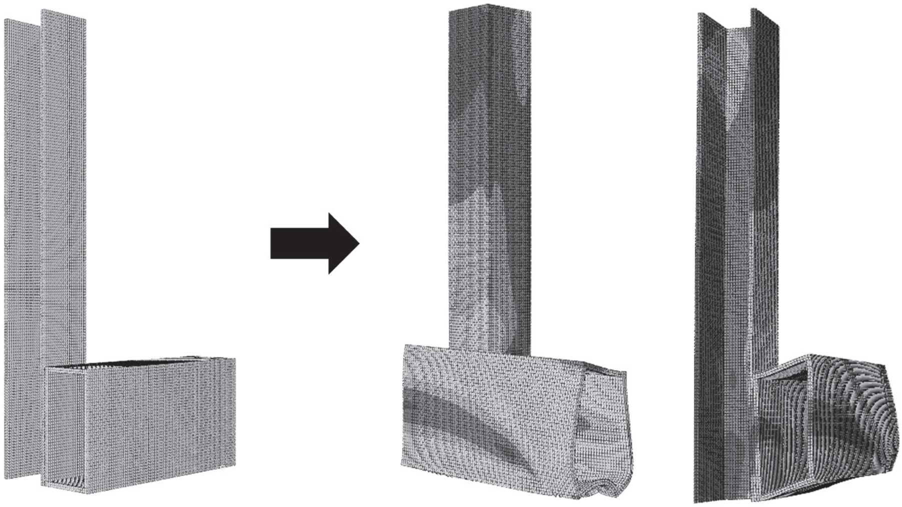

Figure 8.11. Example of a finite element numerical model of a bonded T-joint, showing the mesh and the deformed, stressed shape.

In a classical finite element analysis (FEA), the obtained solution is highly dependent on the mesh size. For example, a coarse mesh with large elements will average the stresses acting on a joint and erroneously show a low stress region near the edges of the overlap length of a SLJ. In contrast, a highly refined mesh (with very small elements near this critical area) will provide a more accurate calculation of the local stress field, (Figure 8.12). However, excessively fine meshes are computationally heavy and it is necessary to find a balance between a mesh that can accurately represent the true stresses acting on the joint and one that is simple enough to be computed quickly.

Besides improving static joint strength, mixed adhesive joints also have the potential to improve the thermal behaviour of bonded joints, ensuring adequate performance under very large temperature ranges. This feature is especially useful for aerostructures of high-speed aircraft and bonded heat shield designs for spacecraft. The greatly expanded thermal range is achieved by combining high temperature resistant adhesives and low temperature resistant adhesives in a single joint (as seen in Figure 8.23). Fortuitously, this combination is perfectly well suited for the mixed adhesive joint concept, since the low temperature adhesives (such as silicones) are inherently flexible and the high temperature adhesives (such as temperature resistant epoxy formulations), are inherently rigid.

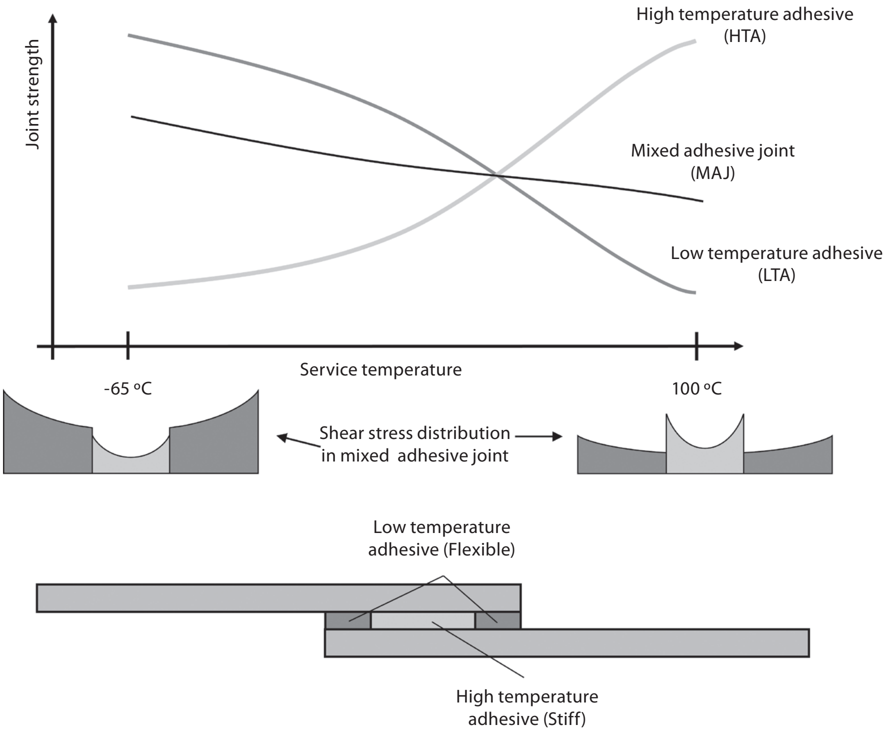

Figure 8.23. Schematic representation of the synergistic effect of combining two adhesives which respond differently to temperature in the same bonded joint.

8.6.3. Functionally graded joints

Graded joints can be seen as an idealized version of the mixed adhesive joint where instead of using a discrete approach, with distinct adhesives, there is now a smooth variation of the material properties. The working principle of a graded adhesive joint is show in Figure 8.24, showing how material properties gradually vary along the overlap.

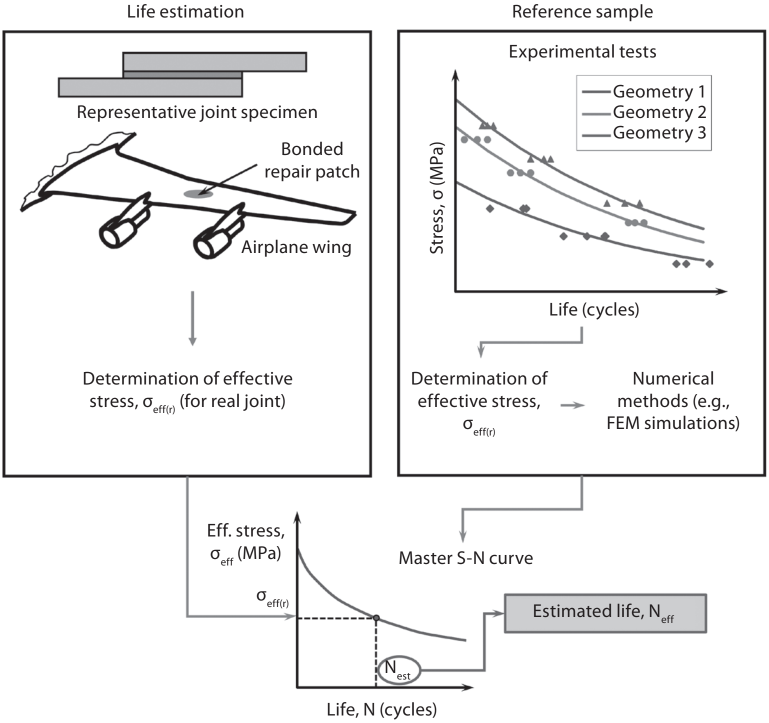

Figure 9.12. Schematic view of the S-N procedure for fatigue life estimation of bonded joints.

The S-N response of the adhesive is also significantly influenced by environmental conditions. Fatigue degradation can be accelerated if the bonded joints are subjected to an aggressive environment, such as exposure to fuel, hydraulic fluid, water, and high or low temperatures. Figure 9.13 schematically shows the effects of different parameters on the S-N response of an adhesive. Constructing a master curve by taking all these effects into account is, of course, a challenging prospect, requiring many characterization tests under varied conditions. Accordingly, the direct method is often more practical for the design of joints subjected to harsh environmental conditions when in service.

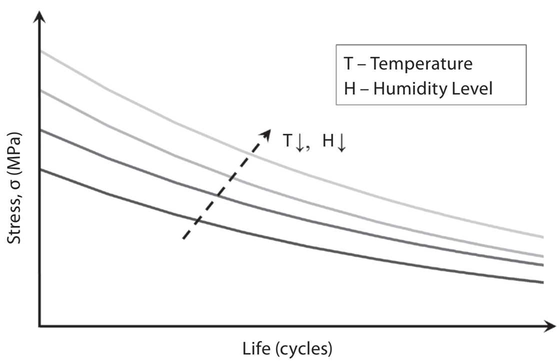

Figure 9.13. Effect of temperature and ageing on the S-N curve of adhesives.

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About the book

This short and focused book provides a description of the fundamentals of adhesive bonding within the field of aerospace applications, aimed at engineering master degree students and all those who wish to learn more about this technology. It highlights the foundations behind the use of adhesive bonding, always within the context of aeronautical cases of use. The book is written to be easily accessible to those with limited knowledge in the field and includes many illustrations to facilitate the comprehension of the concepts exposed. The work is divided into nine chapters, including theory of adhesion, surface preparation, adhesive formulations, joint manufacturing processes, quality control, repair and durability.

About the authors

Eduardo A. S. Marques is a postdoctoral researcher at the Institute of Mechanical Engineering and Industrial Management (INEGI) and guest lecturer at the Department of Mechanical Engineering of the Faculty of Engineering of the University of Porto (FEUP). He obtained his PhD in the area of structural adhesive bonding for aerospace applications at FEUP in 2016 and now studies the effect of high strain rates, extreme temperature and high relative humidity on the behaviour of various materials and bonded structures.

Ricardo J. C. Carbas, is currently a postdoctoral researcher at the Advanced Joining Processes unit, part of the Institute of Mechanical Engineering and Industrial Management (INEGI). He obtained his PhD in functionally graded bonded joints from the Faculty of Engineering of the University of Porto (FEUP) in 2013 and regularly carries out consultancy work for national and international companies.

Alireza Akhavan-Safar is a postdoctoral researcher at the Institute of Mechanical Engineering and Industrial Management (INEGI). He earned his PhD in 2017 in the field of adhesive joints. His postdoctoral research focuses primarily on the durability (hygrothermal ageing and fatigue) of bonded joints both numerically and experimentally. The investigation of the mechanical response of adhesive joints from the fracture mechanics point of view is also part of his research.

A. Francisco G. Tenreiro is a mechanical engineering PhD candidate working on the field of non-destructive testing of adhesive joints. He has obtained his Master thesis in the design and development of a novel Split Hopkinson pressure bar tester for the characterization of bonded joint under very large strain rates. He is the author of several research articles in this field.

Lucas F. M. da Silva is Full Professor in the Department of Mechanical Engineering at the Faculty of Engineering of the University of Porto (FEUP) and editor-in-chief of *The Journal of Adhesion*. He leads the Advanced Joining Processes Unit (AJPU) of the Institute of Mechanical Engineering and Industrial Management (INEGI).

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