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Benefits, Limitations, and Applications of Adhesive Bonding

Even before reading this book, you probably might already have a general idea of the advantages and capabilities of adhesive bonding, but to deepen your understanding of the subject it is necessary to first precisely define the most important concepts, benefits, and limitations associated to the use of this technique. This will allow you, as a user of this technology, to understand all the subsequent chapters of this book and eventually be able to make informed decisions regarding the usefulness of adhesive bonding and implement it in practice.

Skeist and Miron (adhesive technology scholars) first stated in 1981 that adhesives are the diplomats and the most social members of the polymer world. No other technique of joining materials is so versatile and their transversality lies in the ability to unite different materials, in their capability of remaining permanently in the assembly, in the fact that adhesives are user friendly and their success is measurable by a reduction in production costs while maintaining adequate mechanical properties. Although adhesives have been used for millennia, no other bonding technique meets current demands so successfully.

If we look around, we can easily identify applications of adhesives in numerous items of our daily life, showing how this joining technology is an important, yet somewhat hidden, tool in the way we shape our world. Adhesives are found in cutting-edge applications in the mobility sector, where materials are increasingly more complex, lighter, and the associated designs are increasingly bold. The demands of civil construction have also boosted the application of adhesives, and, in recent decades, we have increasingly seen their application in multi-material structures, something which would be virtually impossible to build using traditional techniques. Nevertheless, we also observe the application of adhesives in less demanding applications, such as small gadgets and household appliances that facilitate our daily life as well as clothes and shoes. And as we will see, adhesive bonding is also prepared to play an important role in a new world, more concerned with sustainability and ecological aspects. Today we already have adhesives that meet strict structural demands but also can be produced from materials of biological origin and with a very small ecological footprint, and the use of these materials is expected to grow significantly in the short term.

Introduction to Adhesive Bonding, First Edition.
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1.1 Definition of Basic Concepts

To truly understand the complexity and versatility of an adhesive, we must first clearly define and understand its role. Kinloch, in 1987, defined adhesives as a material which, when applied to surfaces of other materials, can join them together and resist separation, a very rational and synthetic definition of the capabilities of this material. It is, however, necessary to understand that not all adhesives have the same behaviour, and, therefore, it is imperative to differentiate between structural and non-structural adhesives. Adams, one of the greatest impellers of the study of adhesives in the second half of the twentieth century, stated that a structural adhesive is an adhesive that can resist substantial loads and that is responsible for the strength and stiffness of the structure. It is expected that this joint will be stable over the lifetime of the structure, i.e. that its properties will not degrade, that the joint design will be well executed, and that all necessary steps leading to a high-quality bonding joint will be undertaken.

However, if one wishes to be truly knowledgeable in this subject, it is necessary to keep a set of additional basic concepts in mind. So, let us name things as real experts. The adhesive is the substance that initially fills the gap between the materials to be bonded, adheres to them, and solidifies. The materials to be bonded are called substrates and, after bonding, the term generally used is adherend. Between the adhesive and the adherend, the interface is formed. The interface is also designated as the boundary layer and can be defined as the plane of contact between the surface of the two materials (see Figure 1.1).

Adhesives work by exploring the adhesion phenomena. We will study this subject in detail in the following (Chapter 2 - Principles of adhesion), but for now we can define adhesion as the attraction between two substances resulting from intermolecular forces established between them. A joint is the set formed by the adhesive, adherends (or possible intermediate layers as primers), and the interface. A primer is a substance that is used to inhibit corrosion and to improve the level of adhesion with the adhesive and the adherend. In an ideal and well-designed joint, the adherend should always be the weakest part, which means that the presence of the bonded joint does not reduce the strength of the structure.

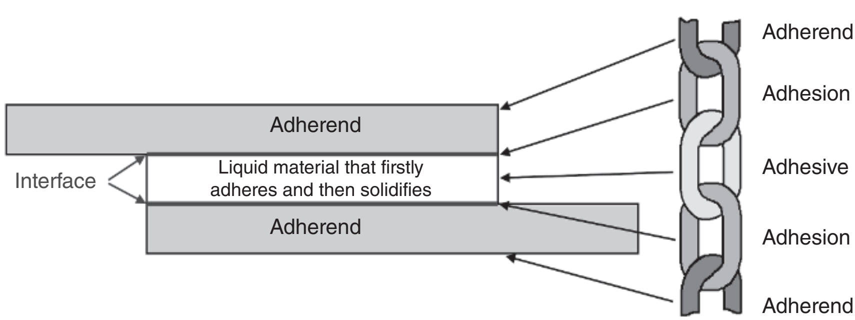


Figure 1.1 Constituents of an adhesive joint.

1.2 Historical Context on Adhesive Bonding

As mentioned before, although the use of adhesives has expanded significantly since the twentieth century, their use actually dates to prehistorical periods. Adhesives extracted from natural sources were used to craft weapons, tools, and decorative objects. Evidence of application of adhesives was found in several excavations, corresponding to quite distinct civilisations (Babylon, Egypt, and the Aztecs), which indicates that the need to join materials was a common necessity for ancient people.

Around 1500 BCE, the Egyptians discovered that tendons, cartilage, and other animal waste could be reused to produce a suitable adhesive for carpentry work. As a testimony to the early historical production of glue and proof of its immense cultural importance, a mural painting was found at the tomb of the vezir Rekhmara in Thebes, which clearly demonstrates men working with this glue. The painting portrays in detail the different aspects of veneer work, including the use of gelatine glue.

The rise of Roman and Greek empires brought about the increased use of adhesives as it was applied in the construction of buildings that are still standing to this day. The art of adhesive boiling was developed further, and the profession of the adhesive cooker was established in Greece at an early stage (and called as Kellopsos). There are several reports in Greek mythology regarding the importance and symbolism given to the adhesives at that time. One of the best-known stories, and with greater emphasis on the strength and weaknesses of adhesives, is the story of Icarus and his father Daedalus using wings built with glued feathers to escape from the Minotaur's maze. Aristotle emphasised in his studies the adhesion properties that can be found in geckos, a very common animal in the Mediterranean. Geckos, like other reptiles, are animals that have the ability to adhere to vertical surfaces.

During this period of history, and due to the geographical proximity to the sea, the techniques for producing adhesives from fish and other animals had become further refined. The Romans were among the first to use beeswax and tar to caulk planking in ships and boats. They extended the range of adhesives in use at that time to include adhesives produced by boiling fish waste. Some of their knowledge has been applied in products used as late as the twentieth century. One example is the application of adhesives extracted from sturgeons in jewellery, where gems were glued to the metal using these adhesives.

However, following the decline of these civilisations and the onset of the Middle Ages, advances in the development of new adhesives halted. Science in general stagnated and the study of adhesives was no exception to this trend. The lifestyle of the populations did not undergo drastic changes until the fifteenth century. Humanity then witnessed a variety of cultural and social revolutions, which would significantly change the course of the study of adhesives, especially during the Renaissance period and the Age of Discovery. At this stage, a widespread use of adhesives in construction work and in the manufacture of furniture emerged, although most applications were still quite conservative in their nature. This period also brought forth some of the first scientific work carried out in this field. Scientists like Galileo Galilei and Isaac Newton were deeply intrigued by adhesives found in nature and attempted to understand how they worked.

Around 1750, the first patent for an adhesive was issued in Britain. This patented adhesive was produced from a fish source, still drawing from centuries-old knowledge. Further patents were then rapidly issued for adhesives derived from natural rubber, animal bones, fish, starch, milk protein or casein. The accelerated development of all these materials was mainly the result of the Industrial Revolution, which triggered technical breakthroughs that saw factories opting for new materials to formulate their adhesives. Cellulose nitrate became the first wood-derived plastic polymer to be synthesised. It was initially used in the manufacture of small items such as ivory billiard balls. Please note that the adhesives created in this era had very limited mechanical strength and were not especially well suited for structural applications. In addition, they were often limited to the geographical availability of some of these raw materials, limiting their globalisation potential.

The first real advances in the drive toward true structural adhesives took place in the late nineteenth century, when the vulcanisation process was patented, and, by 1900, the first adhesives based on synthetic polymers were introduced and quickly became widespread. Creating adhesives from petroleum by-products revolutionised both the versatility and the capabilities of adhesives. Between 1920 and 1940, significant progress was made in this area, but similar to what has been observed to date, structural adhesive applications were still looked upon with some reluctance.

A major revolution in the application and the capabilities of adhesives occurred during the World War II, where new materials were formulated for use in the aeronautical industry. Aircraft and other military equipment were produced at a frenetic pace, and the demands on the components produced reached incomparable requirements. The use of adhesives was expanded to a myriad of structural and non-structural applications, and the rate of creation and manufacture of new adhesives has never slowed down since then. Today, it is unthinkable to conceive our life without using this bonding technology.

1.3 Benefits and Limitations of Adhesive Bonding

You are now aware that the use of adhesive bonding has greatly expanded in the second half of the twentieth century, driven by technological advances in material science and chemistry and gaining popularity due to the important advantages it brings over other well-established joining methods. The most important of these classical joining techniques are based on welding and plastic deformation processes, and to understand why and where adhesives are currently used, we must first discuss a few of the particularities associated with these joining processes.

Let us start by discussing welding, a very efficient and inexpensive technique for joining high-strength metal structures which necessitates the application of large amounts of heat (or energy) to fuse the base and filler materials. It is this heat application that exposes the joined materials to large-temperature gradients, which can change their structure and mechanical properties drastically and severely distort the welded structure. In fact, it is quite difficult to ensure that a welded joint will have strength which is comparable to that of the base material, and furthermore many metallic alloys are simply unsuitable for welding at all. The high temperature also precludes the use of welding in some specific situations, for example in the vicinity of composites or polymers due to the low thermal resistance of these materials. In addition, many welding techniques cannot be used in very limited spaces or for complex geometries and often necessitate additional work to improve the appearance of the welded joint. After welding, the welded joint must be coated by a protective layer (e.g. paint primer or anti-oxidation coating) to avoid corrosion.

Joining via plastic deformation does not require the very high temperatures encountered in welding, as in this case specially designed tools are used to apply large forces that deform metallic sheets and clinch them together in a solid joint. However, the joint geometries that can be created using plastic deformation are quite limited. The large plastic deformations applied to the metal introduce significant stress concentrations on the complete structure, which can lead to early failure. Note that it is also common for plastic deformation techniques to require additional work steps to remove sharp edges that are a by-product of the joining process. Finally, as is the case for the welding technologies, coating with an additional material is often performed to avoid corrosion of the joined materials.

In contrast, adhesive bonding is seen as a more benign joining technique, which does not involve the large temperatures and mechanical loads encountered in welding and plastic deformation joining. This means that adhesive joints allow for more uniform stress distribution. In addition, since this technique relies on an adhesive to establish the connection, it is able to join dissimilar materials, which makes it especially well suited to lightweight, multi-material structures that are now commonly found in vehicle design. Due to the flexibility and excellent damping properties of the adhesive, it is the only joining technique that is capable to bond and ensure the integrity of glass panels (e.g. windshield). Also, it is used in hem-flange to ensure structural integrity and as a waterproof barrier to avoid corrosion.

However, one must never forget the fact that adhesive joining is a relatively new and thus still evolving joining process. New adhesives and bonding technologies are constantly reaching the market and have led to the creation of highly innovative products, with features and capabilities that were unthinkable just a few decades earlier. As an example, we can look into the transportation sector, where designers are always searching for novel joining technologies that enable lightweight construction, essential to meet the challenges posed by the regulatory pressures that demand increased energy efficiency. But the use of adhesives is not limited to transportation industries. Nowadays adhesives are widely used in civil applications, bonding floors and roofs, and in the fixation of structural elements. The flexibility of adhesives absorbs the thermal expansion of the building structures in different seasons, ensuring a durable construction. Even in medicine the use of adhesive is now extensive, where it is used to construct medical devices, used by medical professionals during their interventions, or in products to seal wounds, where bio-adhesives allow for direct contact with human organs. Moreover, adhesives are used in many more applications, joining components in the packaging, electronic, sport, or footwear industries.

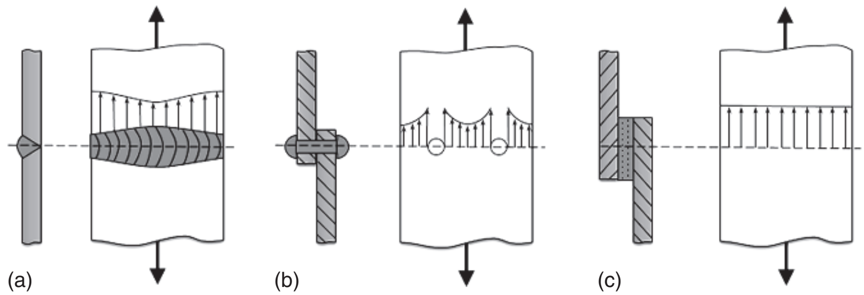


Figure 1.2 Stress distribution as a function of welding (a), riveting (b), and bonding (c) technologies.

Still, please be aware that many in the industrial sector still have some distrust of adhesive bonding, wrongly assuming that this technique cannot provide mechanical performance comparable to other established joining methodologies. This is simply not true as we will repeatedly see in this book.

To summarise, adhesive bonding is a mature, efficient, and unique joining technology that enables the construction of high-performing, highly efficient products. When properly implemented, adhesive joints can:

- Provide a more uniform stress distribution (Figure 1.2);
- Reduce stress concentrations (points which present a high level of stress) as the bond is fully continuous;
- Enable the construction of lighter structures;
- Provide improved fatigue resistance;
- Deliver more flexibility in terms of design and manufacturing processes;
- Allow to join a wide range of materials, including dissimilar materials;
- Be applied over large surfaces, improving the stress distribution and structural stiffness;
- Provide good vibration damping properties;
- Allow for combined joining and sealing properties in one bondline;
- Avoid damaging the fibres in composites with through-holes;
- Ensure no direct contact between the parts to be bonded, avoiding corrosion;
- Provide either electrical/thermal conduction or insulation;
- Be implemented in a fully automated process.

However, some important limitations must be considered when adhesive joints are used, such as:

- The requirement of a careful and suitable selection of surface treatment, especially for polymeric adherends. As we will see, an incorrect surface preparation can have a drastic effect on joint strength;
- Low peel and cleavage strength. Cleavage occurs when load is concentrated at one edge of the joint, while the opposite side remains mostly unstressed. This has the effect of prying the joint open, as if we were inserting a crowbar at the edge of the adhesive layer. Due to this leverage effect, stresses on the adhesive are maximum

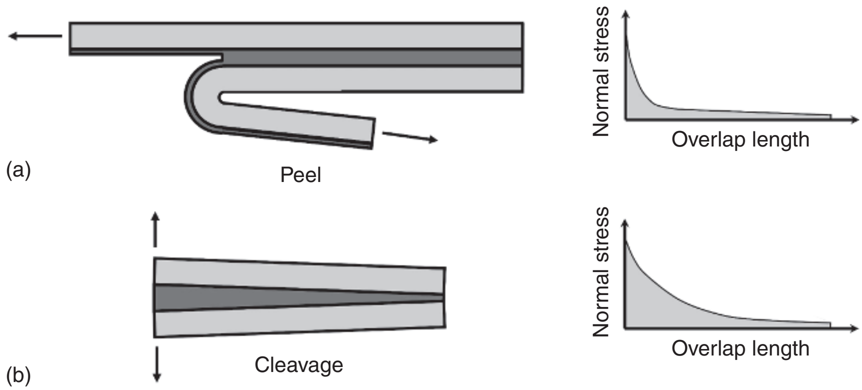


Figure 1.3 (a) Peel and (b) cleavage stresses acting on bonded joints (left) and resultant peel stress distributions (right).

near the area where the cleavage load is being applied and minimal at the opposite end of the joint. It is this concentration of stresses that results in very low cleavage strength. Peel loads are concentrated along a thin line at the edge of the adhesive layer and can only occur where one substrate is flexible.

- The clearest example of the poor peel strength of adhesives is seen in an adhesive tape. If we apply a tape to a flat surface, we will see that it will be very hard to remove if we pull in a direction parallel to the surface. However, should we pull one edge of the tape perpendicular to the surface, we will verify that it is very easy to disbond the tape. In this case, the load we are applying is concentrated just on a very small area. These loading modes are shown schematically in Figure 1.3.
- Limitations with the handling time during manufacturing. This is the time after which the bonded joints can be unclamped and freely moved, as the adhesive has developed enough strength to hold the adherends. In practice, this means that bonded joints are not immediately ready to be handled after manufacturing, which can slow some production processes;
- Special fixture requirements that allow hold together the joined parts during the curing process, also related to the concept of the handling time;
- Difficult disassembly of the bonded parts, which creates challenges both for the repair and the recyclability of bonded parts;
- Low resistance under extreme environmental conditions;
- Wide variation of mechanical properties as a function of environmental conditions exposure.

Due to all these unique characteristics, adhesives are now extensively used in a wide range of industrial sectors, but still it is important to remember that their usage is not only restricted to high-performance structures, such as those in the transportation industry. It is the objective of this chapter to help the reader understand how the use of adhesives has allowed for the growth of new products in these different industries.

1.4 Examples of Current Applications of Adhesive Bonding

1.4.1 Transportation

The constant advances in the highly technological transportation field are usually led by the innovations of road vehicle and aircraft manufacturers. These two industries are the principal promoters behind the development of new manufacturing technologies such as the use of novel high-performance materials (including composite materials) and the practical implementation of highly versatile and high-performance joining technologies. In the last few years, a dramatic reduction of the environmental impact of the transportation industry has been targeted, an effort which necessitates the development of new materials and joining materials. A vehicle, which uses a lightweight construction that employs these techniques, allows for significant weight reduction, decreased energy consumption, and ultimately leads to dramatically reduced emissions. In the following four sections, we will see how adhesive bonding has been adopted by the aeronautical, road transport, and rail industries and the naval industry to achieve these goals.

1.4.1.1 Aeronautical Industry

Before World War II, aircraft were mainly built out of wood, a lightweight, readily available construction material with modest mechanical performance. However, as aircraft performance increased, wood was gradually replaced by aluminium alloys, which was extensively used throughout the second half of the twentieth century. As material science advanced, composites became the new material of choice for these high-performance applications, as they have extremely high specific strength and stiffness, combining low weight with exceptional mechanical performance. However, this transition necessitated the development and adoption of novel joining techniques, as the aluminium structures in aircraft were usually of riveted construction. In the case of composite aircraft, riveting and fastening are problematic and adhesive bonding is preferred. In Figure 1.4, the evolution of the materials used in aircraft construction can be seen. In the last century, aircraft were predominantly built out of metal, but there has been a transition to a structure which is composed of more than 50% of composite materials. And with this dramatic increase in the usage of composite materials, an increase in the use of structural adhesives has also naturally occurred.

The structure of aircraft can be divided into two groups, primary (e.g. fuselage or wings) and secondary (e.g. spoilers or air brakes) structures. The main difference between these two groups is the fact that when a primary structure fails, this will lead to a loss of the aircraft. In contrast, when the secondary structure fails this does not lead to a complete loss and only localised damage occurs. In the first commercial aircraft, the use of composite materials was only possible in secondary structures. However, due to major improvements in manufacturing technologies, new composite materials have been created and are now used in the primary structures of aircraft, supporting the pressurisation loads and the flight cycles (take-off, cruise,

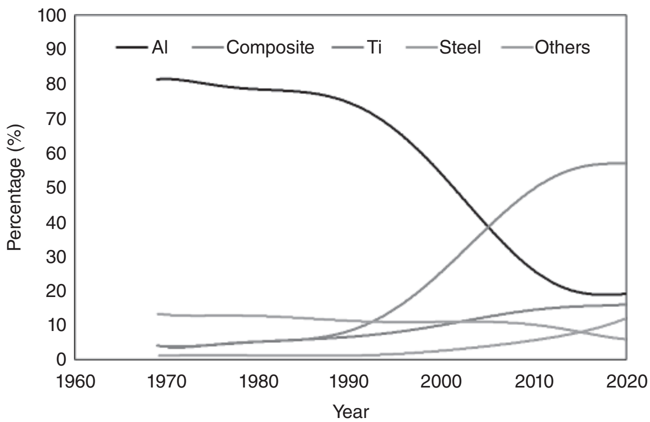


Figure 1.4 Materials used in aircraft construction through the years.

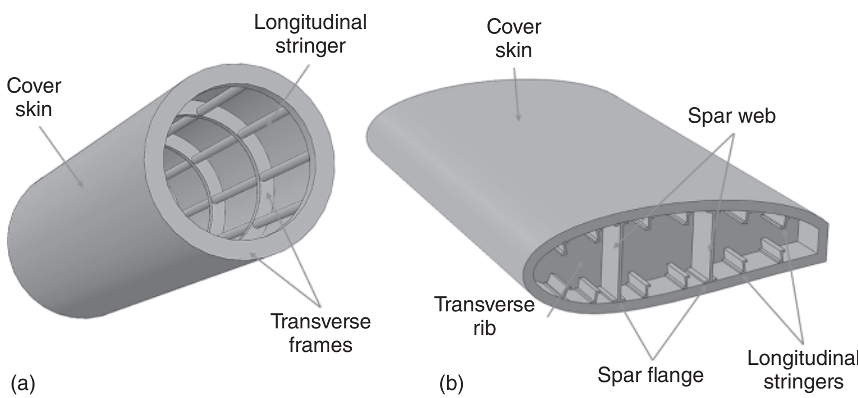


Figure 1.5 An example of a fuselage (a) and wing (b) construction.

and landing loads) and ensuring structural integrity. Adhesive bonding is still mainly used in the secondary structures as the use in primary structures is limited due to the difficulty in detecting weak adhesion using non-destructive tests.

An example of major aircraft structures are the aircraft wings. Here, different adhesive joint configurations can be found, as shown in Figure 1.5. Currently, three different joining techniques are used in aircraft construction (Figure 1.6). These types of joints are mainly used to reinforce the skin of the airplanes, which is achieved by attaching a stringer to a thin sheet of material. In aircraft which use aluminium materials in their construction, riveting is the main joining technology used. However, as stated before, with the increased use of composite materials, adhesive bonding became indispensable to join secondary structures.

In the aeronautical industry, the classical riveting-based joining processes provide a fast inexpensive and effective technique to join materials, with the potential of being easily automated. It is also suitable to join complex dissimilar materials, such as composites and lightweight aluminium alloys. However, riveting requires

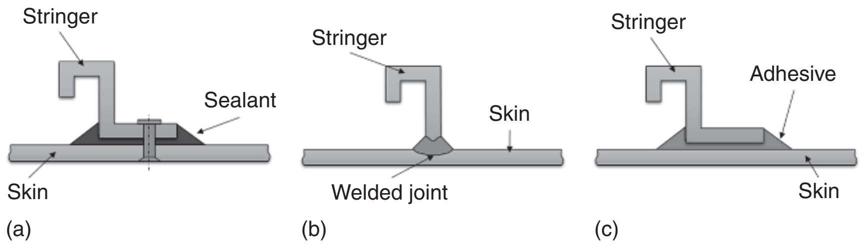


Figure 1.6 Three different joining techniques typically used in aeroplane structures. (riveting (a), welding (b) and adhesive bonding (c)).

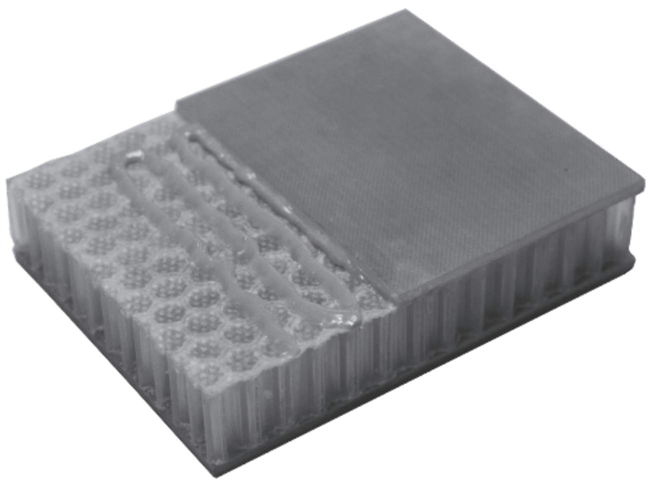
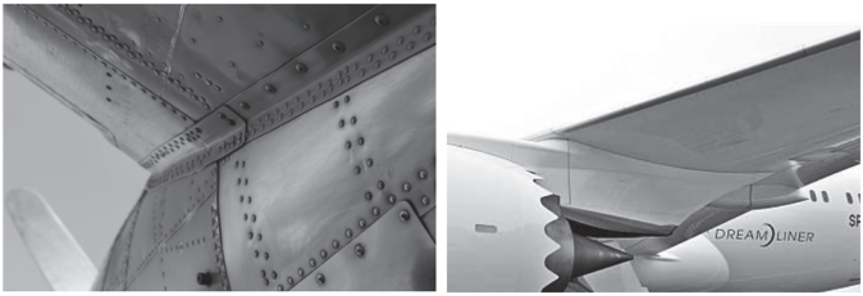


Figure 1.7 A typical sandwich structure used in lightweight composite construction, showing the adhesive used to bond the skin to the core.

drilling many holes, which can be the source of major stress concentrations and require sealants to ensure water tightness. The presence of the exposed rivet heads can also be damaging to the aeronautical qualities of the aircraft, and more expensive flush rivets must be used instead. As a partial alternative, welding is used to join metallic aeronautical components quickly and strongly, although not in the primary flight structures. This is because in these primary structures, many of the lightweight alloys used are in fact very hard to weld. Welding degrades the mechanical properties of the base material, and the large temperatures induced by this process can cause thermally induced distortions in very thin materials typical of structural construction. Thus, adhesive bonding appears as a very powerful alternative for aeronautical applications, allowing to combine dissimilar materials without the introduction of large thermal stresses, free of holes, and other geometrical modifications. It also allows to create innovative materials such as sandwich structures (as shown in Figure 1.7) with a wide range of lightweight core materials and external sheets as well as hybrid laminates, combining metal and composite layers. It also allows to obtain surfaces with good aerodynamic qualities and impermeable to liquids and gases.



(a) (b)

Figure 1.8 Appearance of fuselages constructed using riveting (a) and bonding techniques (b).

However, there are still some limitations in place with the use of adhesives in the aeronautical industry. For example, due to the sensitivity to contamination that this technique has, it is necessary to ensure a clean and inert room during the application of adhesives. There is also a limited understanding by aeronautical designers of adhesive performance in the long term, especially when exposed to service conditions, which include extreme moisture levels and temperature. Lastly, the most important of these limitations for the aeronautical industry is the fact that defects and crack in adhesive joints are very difficult to detect. The available non-destructive testing does not allow to detect certain defects (e.g. weak adhesion), and many regulatory bodies do not allow the use of adhesives in primary flight structures without some sort of additional reinforcement joining method (which can be, for example, rivets).

The performance of aircraft is highly dependent on the aerodynamic efficiency of the fuselage. Figure 1.8 shows the typical appearance of aircraft, which uses mainly riveting and welding techniques in contrast with that of a wing that uses a mainly composite construction. The presence of rivets is quite evident, creating an irregular surface with poor aerodynamic efficiency. In addition, metallic fuselages are also quite susceptible to corrosion and fatigue damage, both of which are potentiated by the holes required by the riveting process. In clear contrast, with a composite construction, the fuselage appearance is visibly much smoother, something which is essential to achieve maximum aerodynamic efficiency. Combined with the low weight of composite materials, this type of construction allows for significant reductions in fuel consumption, which can be up to 25% lower and, consequently, leads to an important reduction of CO_2 emissions.

1.4.1.2 Road Transport and Rail Industry

The reduction of vehicle weight and emissions has been the main goal of the transport industry in the last few decades. The almost exclusive use of steel in transportation structures has now been complemented with the use of lightweight metals (especially aluminium alloys), composites, and polymeric materials. In addition, classical structural joining technologies such as welding or riveting are often replaced or assisted by adhesive bonding technologies. Moreover, given the

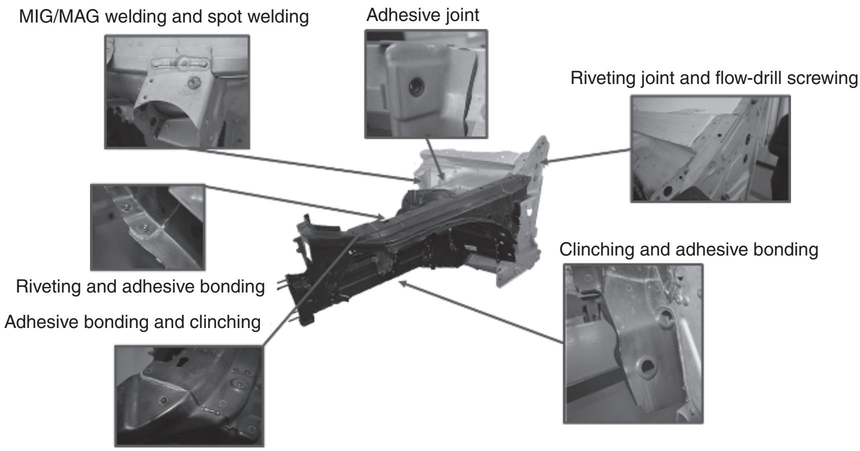


Figure 1.9 Different joining technologies used in some actual body structures.

increased environmental concerns associated with material selection and design, it is now essential to ensure that the end-of-life of vehicle structures has low impact on the environment. This has led to the use of materials with a high level of recyclability and reusability.

Automotive Manufacture The current priority of the automotive industry is to reach major reductions in structural weight, which is only possible with the increased adoption of composite materials. Ultimately, this approach can lead to reductions of up to 70% of the structural weight of the vehicle. If correctly designed, these lighter vehicle structures can have significantly reduced fuel consumption and pollutant emissions, while still ensuring optimal mechanical strength, corrosion, and crash resistance.

The current design trend is to combine different materials in the same structure, such as steel, light metal alloys, composites, or polymers, to create a highly optimised structure. However, this approach necessitates the simultaneous use of many different joining techniques, such as welding, plastic deformation, and bonding (Figure 1.9).

Several welding technologies can be used in a vehicle structure, such as tungsten inert gas (TIG) welding, gas metal arc welding (GMAW), resistance spot welding, laser beam welding, and friction stir welding. Joining techniques based on plastic deformation are also extensively used, such as flow-drill screwing, clinching, grip punch-riveting, semi-hollow punch-riveting, and roller hemming. Often, the roller-hemming procedure is combined with adhesive bonding to avoid corrosion and improve joint appearance and integrity. In this case, besides providing strength to the joint, adhesives act as sealants.

As stated before, there has been also an increase in the use of composite materials in vehicle body structures. A good example of this trend is seen in some electric cars, where the total weight of the body structure is only 150 kg. Two main construction approaches are combined in this structure. The first is the use of lightweight

(a) (b)

Figure 1.10 Two examples of heavyweight public transport ((a) bus and (b) train).

materials to reduce the weight and the second is the use of recycled materials to reduce the ecological footprint. For this type of construction, given the materials being used, the only suitable joining technology is adhesive bonding.

Rail and Bus Manufacture Buses and trains have until recently been exclusively made with steel structures and panels, joined using welding, riveting, and fastening. This has led to heavyweight vehicles with high fuel consumption and with high level of emissions (Figure 1.10). Due to newly imposed environmental regulations and the cost of fuel, combined with the development of new light materials, the materials used in these vehicles have progressively changed to light materials to increase efficiency and decrease the emissions.

Concurrently, there is now an important trend toward the use of electrical propulsion for public transportation, which, due to the weight of the batteries used, is only practical with the extensive use of lightweight materials in the body structure. To reduce the cost of producing these structures, vehicles are constructed in as few steps as possible. For example, the main panels and roof are constructed as individual modules to be integrated in the full structure. To assemble the different parts and elements, which include metals, composite materials, and glass, adhesive bonding is the technology that allows for optimal mechanical performance (good mechanical properties and damping properties) and efficiently join different materials. Adhesives are extensively used to join floor structures, side panels, roof structures, and windows, as can be seen in Figure 1.11.

1.4.1.3 Naval Industry

The ships that are used for fishing and cargo transport are mainly built out of steel components, assembled using welding. The construction of these boats is also modular, divided into smaller subsections that are later joined by welding and fastening in a final assembly step (Figure 1.12). As stated before, when welding is used the high temperature generated causes significant distortion of the pieces to be joined. For