JOINING OF FIBRE-REINFORCED POLYMER COMPOSITES

A Good Practice Guide

NATIONAL COMPOSITES CENTRE

Composites UK
Trade Association

TWI

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1. INTRODUCTION

There is a need for the composites designer or engineer to consider the various joining solutions available at an early stage and understand the advantages and disadvantages of each potential technique. Designers, manufacturers and clients need sufficient information to engage with joining experts in order to create the most effective joining strategy possible.

Note: Readers new to the subject may find Appendix A Glossary and Terminology a useful reference.

1.1 Scope

This document addresses good practice for joining composites. It offers information on the types of joining processes available and gives recommendations on how they should be carried out. Advice on testing, both non-destructive (inspection) and destructive, is provided so that the users can determine the performance of the joints. This guide is not intended to offer detailed advice and specifications for testing, or to instruct the reader on the best joining solution for any specific application.

A composite material is composed of at least two materials, which combine to give properties superior to those of the individual components. CMH-17[1] defines a composite material to be: “a combination of materials differing in composition or form on a macroscale. The constituents retain their identities in the composite; that is, they do not dissolve or otherwise merge completely into each other although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.” This good practice guide refers primarily to fibre reinforced polymer (FRP) composites, usually with carbon, glass, aramid, basalt, polymer or natural fibres embedded in a polymer matrix. Both thermoset and thermoplastic matrix composites are covered but metal and ceramic matrix composites are considered a sufficiently different group of materials to be excluded from this guide.

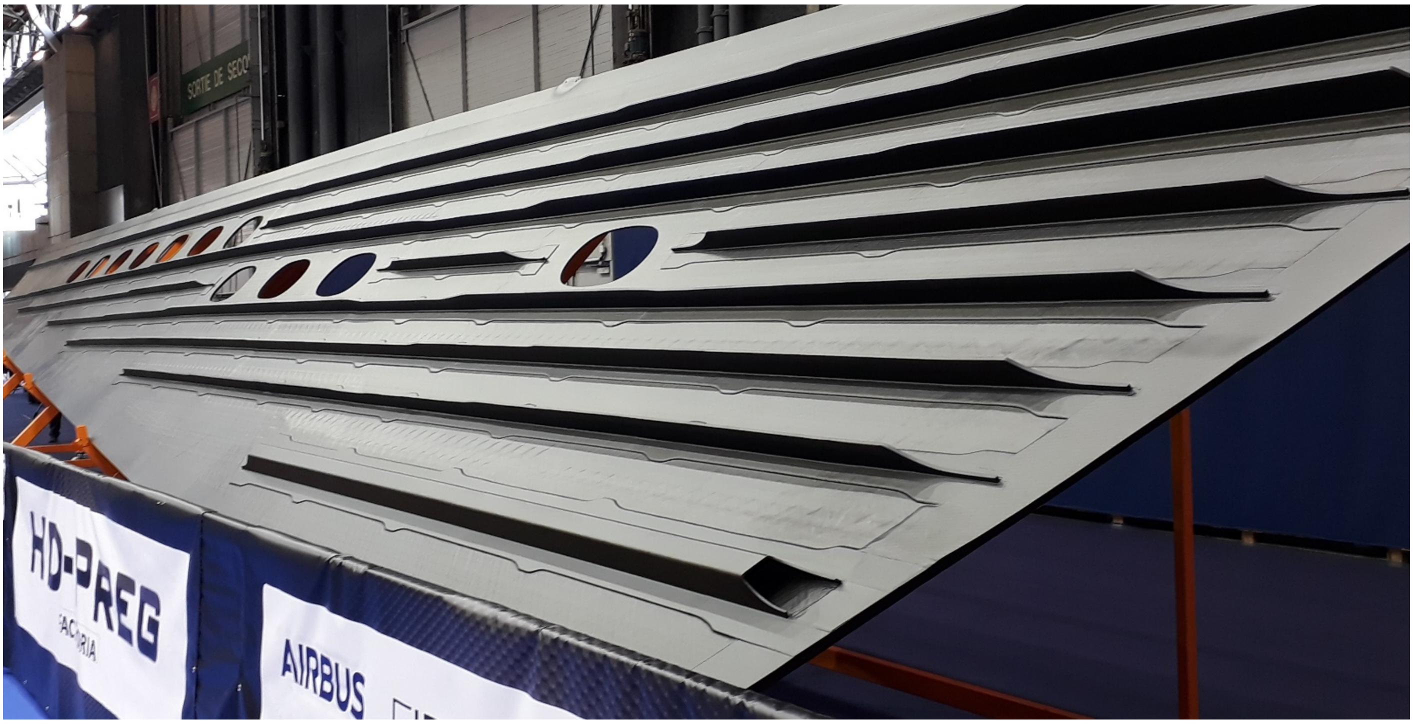

Figure 1: A380 empennage horizontal tail plain structure with co-cured stringers, negating the need for post-cure joining. Photo: Composites UK (at JEC 2019)

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[1] SAE International, 2017: ‘Composite Materials Handbook, Volume 3, Polymer matrix composites materials usage, design, and analysis’. CMH-17-3G Volume 3

1.2 Joining in design and specification

The best joining solution for each specific application needs to be determined based on many factors, such as the desired production volume, available budget, availability of capital equipment and required joint performance.

The performance of any joint should be determined in order to ensure that it is fit for purpose and complies with all relevant design codes and specifications. Joining has traditionally been considered a secondary process; the selection of the joining technology only being considered after design and manufacture of the parts intended to be joined. This approach has often led to problems downstream that could easily have been avoided if joining had been considered at the very early design stages. Early consideration of joining strategies allows the selection of materials and overall design to facilitate the joining mechanism, whilst maintaining structural performance and other design criteria, rather than potentially compromising the system.

2. GOALS AND CHALLENGES

2.1 Do we need joining at all?

Joining any structures inevitably means joining materials, and the challenges of today's multitude of different materials and material combinations makes the whole joining process something to be carefully considered before proceeding. Many factors need to be considered and problems solved, ultimately consuming significant time and financial resources. It is therefore prudent at this point to pause and consider the reasons for joining and whether manufacturing the structure or component without joints, as a single part, is a better approach.

Composites offer the designers the potential for near net shape manufacturing. The fact that the composite material itself is, in general, manufactured at the same time as the part (the obvious exception being thermoplastic composites made from press-formed pre-manufactured sheets) simplifies the manufacture of complex 3D structures. This approach is in many ways similar to metal casting, where complicated shapes can be made as a molten metal flows to fill the cavities of a mould. Composites production processes such as Tailored Fibre Placement (TFP) are capable of producing intricate parts (Figure 2) that can place fibres in the precise paths required for optimum mechanical performance. This process can, in theory, be applied to a range of size parts depending on the size of the individual fibre tows and the capability of the equipment used to place them.

Figure 2: Leibniz Institute of Polymer Research (IPF, Dresden, Germany), the inventors of TFP, produced the preform for this stool using the process. Photo: IPF

2.2 Reasons for joining composites

It would appear, therefore, that all composite structures can be manufactured as a single part, negating the need for joining of any sort. Indeed, an ideal structure might seem to be one without any sources of local weakness or additional weight imposed by joints. However, there are many good reasons for joining, and the motivation for joining may then influence the selection of the best joining process.

There are four accepted goals for a successful design to be realised:[2]

- Functionality
- Manufacturability
- Cost

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[2] Ashby M F, 1999: 'Materials Selection in Mechanical Design'. 2nd ed., Oxford, United Kingdom. Butterworth-Heinemann, pp. 1–7, 13–14, and 246–280, 1999

- Aesthetics

The relative importance of these four goals can be discussed at length and will vary depending on the application being considered, but they can be summarised as in the following sections.[3]

2.2.1 Functionality

Any joint must achieve the desired element of functionality, as expressed by its ability to:

- Carry or transfer loads in an array of parts needing to act together without moving (static structure)
- Carry and transfer loads in an array of parts needing to act together by moving (dynamic structure)
- Achieve size and/or shape complexity beyond the limits of primary fabrication processes (casting, moulding, forging, forming, powder processing, etc.)
- Enable specific functionality demanding mixed materials
- Allow structures to be portable (i.e., able to be moved to or from sites)
- Allow disassembly for ultimate disposal
- Allow disassembly for maintenance and repair operations
- Provide better impact damage tolerance in the structure than is inherent in the materials (i.e., structural damage tolerance)

2.2.2 Manufacturability

It is also an obvious goal that any join must facilitate manufacturability:

- To obtain structural efficiency through the use of built-up details and materials
- To optimise choice and use of just the right materials in just the right place
- To optimise material utilisation (minimise scrap losses)
- To overcome limitations on size and shape complexity from primary fabrication processes
- To allow on-site erection or assembly of prefabricated details

2.2.3 Cost

Minimising costs if often considered as a high priority as a joining goal:

- To allow optimal material selection and use (versus forcing compromise)
- To maximise material utilisation and minimize scrap losses
- To keep the total weight of materials to a minimum (through structural efficiency)
- To provide more cost-effective manufacturing alternatives (versus forcing a primary fabrication process to its limit)
- To facilitate automation of assembly, for some methods
- To allow maintenance, service, repair, or upgrade; all of which reduce life-cycle costs
- To facilitate responsible disposal

2.2.4 Aesthetics

Aesthetics are very important in some cases. Composites can offer designers potential to exploit the inherent beauty of the materials, and:

- To enable application of veneers, facades, etc., different from the underlying structure
- To allow complex shapes to be formed

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[3] Messler R W Jr, 2004: Joining of materials and structures: From pragmatic process to enabling technology'. Elsevier Butterworth–Heinemann, ISBN: 0-7506-7757-0, pp14

2.3 Challenges

Joining of composite materials, compared to other materials such as metals and ceramics, presents a unique challenge: providing a joint performance and functionality equivalent to the parent material. Composites are unique in that the continuity and integrity of the fibres is difficult to maintain through the joint.

The performance of a structure or an assembly is critically dependent on the behaviour of any joints it contains, and the very reason that composite materials may have been chosen in the first place may be lost if effective methods for joining cannot be found[3]. Although the continuity of fibres is typically compromised across a composite joint, few techniques attempt to re-join the reinforcement in the joint, relying primarily on joining the matrix material and allowing the loads to be transferred through to the fibres.

Taking a ‘black metal’ approach to joining, where techniques developed for metallic joints are simply transferred to composites, can be a mistake and before beginning the process of joining composites a good background understanding of the unique properties and behaviour of composites is recommended.

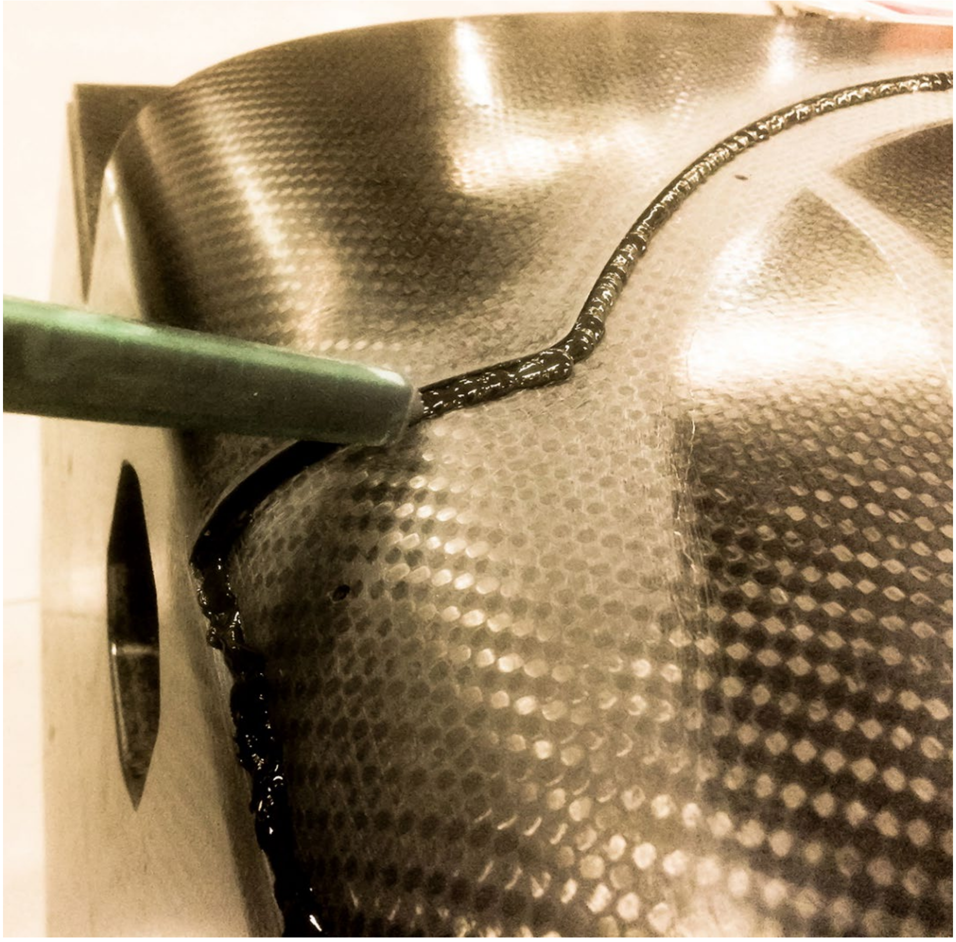

Figure 3: Permabond ET5429 high strength two part epoxy adhesive, colour matched for carbon fibre, applied to CFRP vehicle body panels. Photo: Permabond

3. JOINING POSSIBILITIES

3.1 Types of joints

It may seem obvious that the purpose of a joint is to connect two or more objects to make a single entity, however the precise nature of the joint is more versatile. Joints can be flexible: hinges and drawer slides, universal joints, and bearings; or they can be fixed: buildings or other immovable structures. The required permanency of a joint is also a variable. Some joints are designed to last for a very brief period, such as the many joints making up missiles or explosive devices, where the joints don't require disassembly, and disassembly for recycling is not an issue. Others must last indefinitely, for example space exploration probes which contain structural joints that are designed to last the mission duration with no requirement for the joints to ever be taken apart. Joints can also be single use: food packaging, envelope seals, tamper-proof seals; or multiple use: inspection covers, screwed bottle tops, box lids, zips, buttons, press-studs. Additionally, some are designed to be permanent for the anticipated life of the structure, but then must be easily disassembled at the end of the product's life to facilitate recycling. Before the joining process begins all these must be considered as the choice of joining process may be strongly affected by its life and permanency, and how it will operate.

3.2 Joining techniques

Joints can be categorised in relation to the three fundamental forces employed to affect the joints: mechanical, physical and chemical.[4] However, these are more commonly classified into mechanical fastening, adhesive bonding and welding. This breakdown is, perhaps, more familiar to composite manufacturing organisations who have less interest in the forces involved in the joining processes. Within these three broad categories, soldering and brazing are covered under the welding title, and mechanical attachment/interlocking is considered as a form of mechanical fastening.

Fortunately, despite the existence of only three categories of joining technologies, many varieties are available within each category (Figure 3). As a result, there is seldom a joining process that cannot be found for any given application. The problem is often how to decide upon the best joining solution for a particular application, as this decision often involves an element of compromise between conflicting requirements such as performance, weight, time and cost.

Figure 4: Summary of a selection of joining processes: bonding, welding and fastening

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[4] Messler R W Jr, 2004b: 'Joining Composite Materials and Structures: Some Thought-Provoking Possibilities'. Journal of Thermoplastic Composite Materials 2004 17: 51

4. MECHANICAL FASTENING

4.1 Introduction

Mechanical fastening has been in widespread use as a joining technique ever since the human race first realised the possibilities that joining different things together offered, either as means of providing improved shelter or to increase the efficiency of weapons used to hunt prey or defend against attack. As materials have developed, and through the growing introduction of composites since the 1960s, designers have been tempted to adopt the established, historical mechanical fastening rules and guidelines. However, experience has shown that this may not be the best approach, and the doubts over the ability of these relatively new materials to withstand fibre damage during cutting and drilling, the complex effects relating to anisotropy, and the lack of any real plasticity and yielding have tempered this initial enthusiasm. Engineers are still learning, through the continuing efforts of researchers in the field of composites, how to accommodate the peculiar properties of these anisotropic materials into the design of efficient and safe structural joints.

Fortunately, confidence in composite joints has grown sufficiently for them to be accepted for many applications in just about all industry sectors, including automotive (Figure 5), oil and gas (Figure 6) and aerospace (Figure 7).

Figure 5: Composite drive shaft containing mechanically fastened joints at each end. Copyright © 2020 TWI Ltd reproduced with permission

Figure 6: Mechanical interlock joint in a GFRP pipe. Copyright © 2020 TWI Ltd reproduced with permission

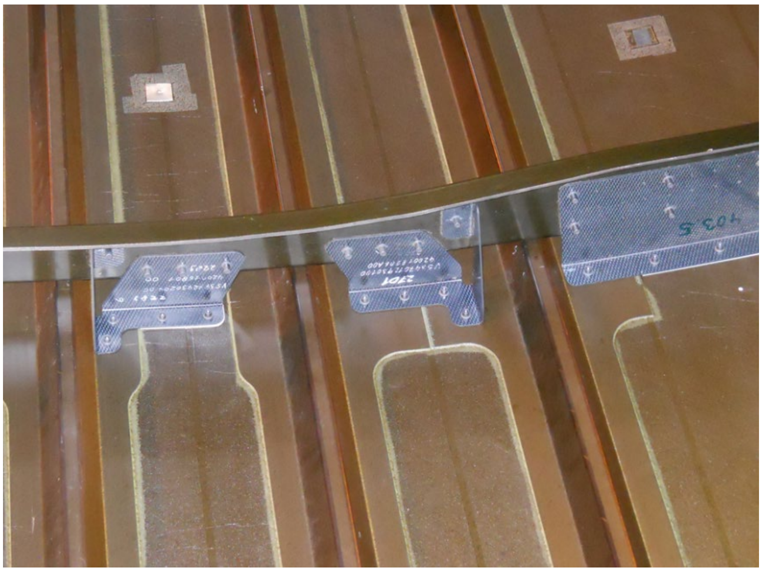

Figure 7: Mechanical fastening in a commercial aerospace application (fuselage). Copyright © 2020 TWI Ltd reproduced with permission

4.2 Mechanical attachment

Mechanical attachment requires no third body fastener, and therefore no hole is required. Instead, the geometry of the parts being joined is designed to provide the mechanical interlocking required to resist loads through the joint. Geometric features can be either locking features; designed to lock parts together, or locating features; primarily designed to compensate for manufacturing induced variations and tolerances.[5] This branch of mechanical fastening is, perhaps, less useful for joining composites due to the complexity of moulding in the interlocking features on the surface of the parts. It is more likely to be found joining unreinforced thermoplastic parts.

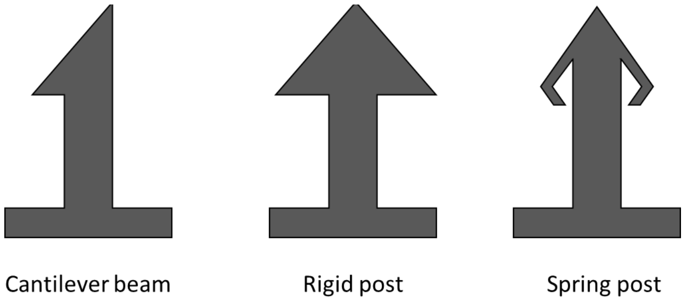

Figure 8: Three examples of locking features for mechanical attachment (Adapted from Messler, 1997 [5])

Other forms of mechanical attachment such as cinching and clinching are not generally applicable to composites as they rely on significant plastic deformation and flow of the materials to form the joint; behaviour that is not typical of composites.

4.3 Mechanical fasteners

Mechanical fasteners are generally regarded as nuts and bolts or rivets; joints where a separate fastener is inserted through the materials being joined in order to transfer the loads. This category of joining generally requires a hole to be made in all parts being joined, into which the fastener is inserted. The exception to this is where a fastener is embedded and co-cured into the composite part, or where it is bonded onto the part with adhesive.

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[5] Messler R W Jr, Genc S and Gabriele G A, 1997: 'Integral attachment using snap-fit features: a key to assembly automation. Part 3 – an attachment-level design methodology'. Assembly Automation, 17, 3, 1997 pp239-248

4.3.1 Special fasteners for composite structures

Fasteners can be separated into two main categories; permanent (where the fastener is in place for the entire life of the structure) and removable (where the fastener needs to be replaced at some point for access or maintenance operations), depending on the life expectancy of a structure.

Hi-Lok™ and lockbolt fasteners are commonly employed for permanent installations in composite aircraft structures. The Hi-Lok is a threaded fastener that incorporates a hex key in the threaded end to oppose the torque applied to the collar during installation. The collar is made of a frangible part that separates at a predetermined torque value. The lockbolt is comprised of a collar that is swaged into annular grooves, and can be of two types; pull-type or stump-type. Installation of the Hi-Lok and the pull-type lockbolt can be performed by one machine from one side of the structure. In contrast, the stump-type lockbolt needs support on the head side of the fastener to react against the swage, and is therefore only used where both sides are accessible.

Another fastener commonly used for carbon fibre composite components is the Eddie-Bolt®, which is similar to the Hi-Lok fastener. If not controlled, the clamping force during fastener installation can cause a deformation of the matrix and a potential pull-through fastener failure after repeated loading.

If the reverse side is inaccessible during assembly then one solution is to use ‘blind fasteners’, such as pop rivets, or nut plates, which grip the nut to the rear face. Blind fasteners can be divided into two categories: threaded-corebolt-type and pull-type. The threaded-corebolt type has the highest clamping force capability (important for joint fatigue strength), little relaxation at the end of the installation cycle, and reduced bolt-bending phenomenon. The pull-type blind fastener has a lower clamping force, so may offer lower performance, but is quicker to install, lighter and less expensive. If the mechanically fastened composite parts must be removable and the access is just from one side, nut plates are recommended rather that blind fasteners, although it has been suggested that nut plates offer an inferior performance compared to blind fasteners.

Further guidance can be found in Parker (2001) [6] and Niu (1992) [7].

Adjustable sustained preload, or ASP®, fastening systems are used for joining composite sandwich structures containing soft cores such as honeycomb or foams. An alternative widely used approach is to use a potting compound to fill the cell where the fastener will pass through.

bigHead® fasteners are a way to provide secure fixing or fastening points on or within a composite material, typically without the need for machining or drilling. bigHead fasteners are especially appropriate in applications where it is not desirable, or permissible, to have a through-hole in the composite material, or visible trace of the fastening on the A-surface. The large head part provides the attachment, or anchoring, for the fixing and fixings are available in a variety of forms and sizes. It is possible to embed or integrate bigHead fasteners into composite materials and manufacturing processes (co-process, see Figure 9), and embed them into or attach them onto components (post-process).

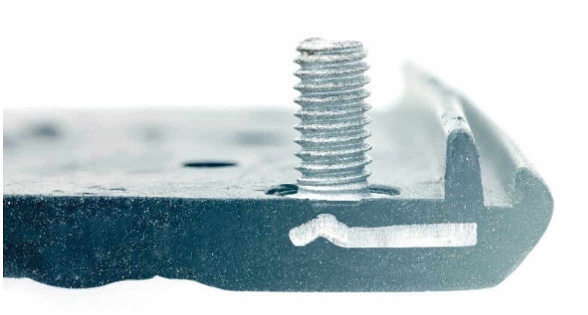

Figure 9: Example of embedded bigHead® (co-processed integration). Photo: bigHead Bonding Fasteners Ltd

Figure 10: Example of adhesive bonded bigHead® (post-process integration). Photo: bigHead Bonding Fasteners Ltd

Adhesive bonding (see Figure 10) is a common post-process attachment method for bigHeads in composite material applications. Key considerations when specifying bigHead fasteners are whether

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[6] Parker R T, 2001: ‘Mechanical Fastener Selection’. ASM Handbook Volume 21, Pages 651-658

[7] Niu M C Y, 1992: ‘Composite airframe structures’. Hong Kong Conmilit Press Ltd

one requires co-process or post-process integration, the available space within the assembly, the mechanical loading expectation, the tighten-up torques and component clearances during assembly, and selection of the appropriate material and coating for the given application. To determine the most suitable bigHead solution for a given application, it is best practice to discuss these considerations with the fastener supplier or manufacturer prior to selection or design finalisation.

4.3.2 Types of fastener material

Two main classes of fasteners used to join composites parts are metallic and non-metallic.

The strength offered by non-metallic fasteners is adequate for lightly loaded structures. Highly loaded structures still need metallic fasteners.[20]

4.3.2.1 Metallic fasteners

The choice of metallic fasteners depends mainly on the environmental compatibility of the fastener and the laminate material in order to avoid galvanic corrosion. When fastening carbon fibre reinforced polymer (CFRP) in particular, fastener materials such as titanium, corrosion-resistant steels (CRES), nickel and cobalt alloys are used in order to prevent galvanic corrosion.[16] [20] [8] Stainless steels, Monel and precipitation hardening (PH) stainless steels are alloys which can be used with caution. Aluminium, magnesium, cadmium and low alloy steels are not compatible with CFRP and their use can be taken into consideration only if reliable coatings are used.

4.3.2.2 Non-metallic fasteners

Non-metallic fasteners are made of reinforced thermoset and/or thermoplastics. The main advantages of non-metallic fasteners are:[16] [20]

- Elimination of dissimilar material corrosion
- Reduction of weight
- Use would avoid fuel tank arcing during lightning strike
- Electromagnetic transparency

4.4 Machining of fastener holes

The holes that are a prerequisite for mechanical fastening can be formed during the composite manufacturing process, by a tow placement/tow steering operation, or by positioning a dry fabric preform such that fibres are displaced around a shaped feature in a tool in a resin infusion process (windowing). Post-manufacture holes, made through material removal techniques such as drilling and milling ('machining') after the composite parts have been manufactured, are more common as they allow flexibility in positioning the fasteners at any time during the life of a product, and can compensate for mismatch and manufacturing induced geometry variations.

However, these machining processes can lead to problems. During machining, defects such as delamination, fibre damage, surface damage and thermal degradation can be introduced into the composite parts, which can reduce the performance and the reliability of the structure. Machining technology can be categorised into mechanical methods (those using direct contact between a tool and surface) and non-mechanical methods (those using a cutting jet or beam of radiation). A brief review of cutting composites is helpful in understanding the potential defects, and subsequent inspection required, when selecting mechanical fastening as a joining approach.

4.4.1 Mechanical machining

The typical defects that can be introduced within the workpiece during mechanical machining:[9]

- Delamination: Separation of bonded composite plies which may occur at the drill entry and at the drill exit

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[8] Schwartz M M, 1992: 'Composite materials handbook'. Published by McGraw-Hill, Inc.

[9] Paleen M J and Kilwin J J, 2001: 'Hole Drilling in Polymer-Matrix Composites'. ASM Handbook Volume 21, Pages 646-650

- Splintering/fibre breakout: When fibres break free from the surrounding resin matrix. This may occur at the drill entry or exit, particularly in unidirectional materials
- Fibre pull-out: Tearing or breaking out of fibres within a hole or machined edge
- Microcracking: The creation of small cracks in the resin surrounding the fibres
- Heat damage: Present in the form of visual discoloration or partial melting or charring of material surrounding a hole. Generally, heat damage is worst on the drill exit side

The severity of the various defects is controlled by parameters associated with the tools (tool geometry, tool material) and those related to the cutting operations (in particular cutting speed and feed rate).

Delamination is the main problem associated with drilling of fibre reinforced composite materials, causing a reduction of the structural integrity of the materials.[10] Two mechanisms of delamination associated with drilling composites are observed: push-out at the drill exit and peel-up at the drill entrance. Delamination force is closely related to drill thrust so reducing the thrust force during drilling reduces delamination.

4.4.1.1 Tool geometry

Tool geometry plays a significant role in thrust force, and the main parameters which affect drilling performance are summarised in Table 1.

Table 1: Tool geometry parameters and their effect on making holes in composites

Parameter	Effect
Point angle	Thrust force increase with increasing point angle. A smaller point angle is a better choice for drilling composite materials.[11]
Helix angle	A larger helix angle generates less thrust force and torque, and consequently generates less delamination.[12]
Diameter	Using a smaller diameter drill bit gives less delamination.[13]
Chisel edge geometry	The use of special drill bit designs, for example to reduce the indentation effect of the chisel edge, can decrease the risk of delamination.[14]

4.4.1.2 Tool material

The quality and performance of the machining processes are also directly related to tool wear. A wide range of cutting tool materials are available, and are generally characterised by hardness, strength and toughness.[10] Examples of typical cutting materials include:

- High speed steel (HSS)
- Cemented carbides
- Ceramic

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[10] Sheikh-Ahmad J Y, 2009: ‘Machining of Polymer Composites’. Springer Science+ Business Media

[11] Shyha I S, Aspinwall D K, Soo S L and Bradley S, 2009: ‘Drill geometry and operating effects when cutting small diameter holes in CFRP’. International Journal of Machine Tools and Manufacture 49, 1008-1014

[12] Gaitonde V N, Karnik S R, Rubio J C, Correia A E, Abrao A M and Davim P J, 2007: ‘Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites’. Journal of Material Processing Technology 203, 431-438

[13] Sonbaty E I, Khashaba U A and Machaly T, 2004: ‘Factors affecting the machinability of GFR/epoxy composites’. Composite Structures 63 (3–4), 329–338

[14] Tsao C C and Hocheng H, 2003: ‘The effect of chisel length and associated pilot hole on delamination when drilling composite materials’. International Journal of Machine Tools and Manufacture 43, 1087–1092

- Super-hard materials

These four materials, their properties and applications, are summarised in Table 2.

Table 2: Tool materials properties and their applications to composites

Material	Properties	Applications
High Speed Steel (HSS)	Highest toughness Moderate strength Low to moderate hardness Inability to retain hardness at high temperatures	No suitability for high-speed machining Not recommended in machining of abrasive materials such as FRPs
Cemented Carbide (WC-Co)	Moderate toughness Moderate hardness Ability to retain their properties at high temperatures Chemical wear at high cutting temperatures	Moderate hardness does not permit long life during machining advanced and highly abrasive engineering materials, but WC-Co has become a standard material for machining composites
Ceramic	Poor toughness Moderate hardness Highest thermal stability Low thermal conductivity	Not suitable for machining fibre composites; tendency to fail by chipping and the inability to be produced in sharp shapes
Polycrystalline diamond (PCD), Diamond coated carbide	Highest hardness Low to moderate toughness High strength Good thermal conductivity Low coefficient of friction	Able to machine from moderately to highly abrasive materials

4.4.1.3 Cutting parameters - feed rate and cutting speed

Delamination is also strongly affected by the cutting parameters, particularly the cutting speed and the feed rate. There is an increased likelihood of delamination with an increased feed rate.[15] However, when compared with feed rate, the effect of cutting speed on delamination is relatively low. The relationship between the two cutting parameters (feed rate and cutting speed) and the performance of the process is complex and highlights the difficulty in recommending a ‘best’ condition that can be applied generally to all fibre composite materials and operations. Each material and application should be considered on a case by case basis.

4.4.2 Non-mechanical machining

Other, less common, techniques can be used to make fastener holes:

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[15] Davim J P and Reis P, 2003: ‘Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments’. Composite Structures 59, 481-487

- Abrasive water-jet machining (AWJ)
- Laser beam machining
- Water-jet guided laser
- Electrical discharge machining (EDM)
- Ultrasonic machining (USM)

The process parameters for each of these techniques will affect the quality of the hole and performance of the fastened joint.

Figure 11: Water-jet cutter head. Photo: National Composites Centre

4.5 Failure modes

There are three basic failure modes in mechanical composite joints under conditions of plane loading:[16]

- Net-tension/tension failure
- Shear-out failure
- Bearing failure

Additionally, mixed types of failures can occur, such as:

- Cleavage tension (caused by mixed tension/shear)
- Bolt-head pulling through the laminate (especially with deeply countersunk holes)
- Bolt failure due to bearing failure

Figure 12 illustrates some of the key failure mechanisms highlighted above.

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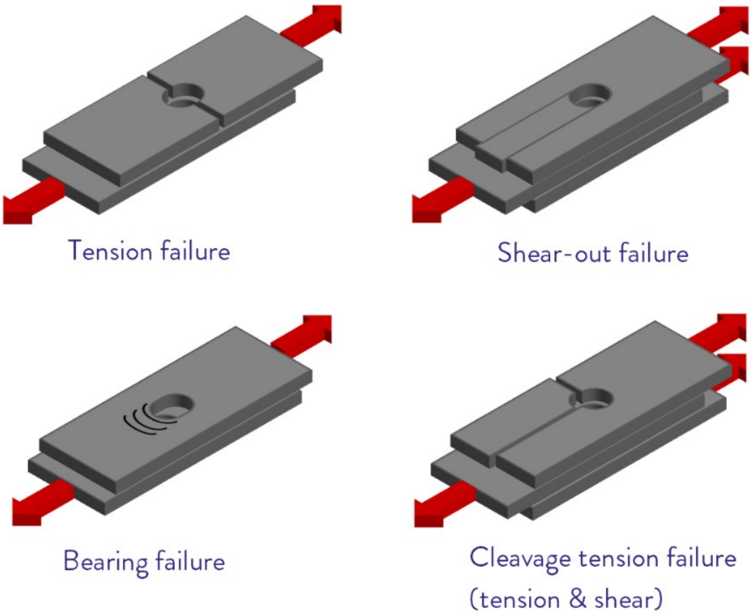
[16] Baker A, Dutton S and Kelly D, 2004: 'Composite Materials for Aircraft Structures'. Second Edition. AIAA Education Series


Tension failure

Shear-out failure

Bearing failure

Cleavage tension failure
(tension & shear)

Figure 12: Schematic of four of the main failure modes in mechanical joints in composites

Matrix and fibre tension failures caused by stress at the bolt-hole edge usually lead to net-tension failure and, typically, this occurs when the w/d ratio (Figure 13) is small. Shear-out and bearing failures are principally a consequence of the shear and compression failures of fibre and matrix. Net-tension and shear-out failures are sudden and catastrophic. Bearing failure occurs when an exaggerated deformation of the hole is reached. It is a gradual and progressive failure mode, and because of its non-catastrophic nature, bearing failure often has less serious consequences than the other failure modes. Furthermore, shear-out failure is more complex than net-tension failure because of the complicated multi-axial stress state in the shear-out failure region adjacent to the bolt-hole, which is the reason why the shear-out failure region is difficult to predict accurately.

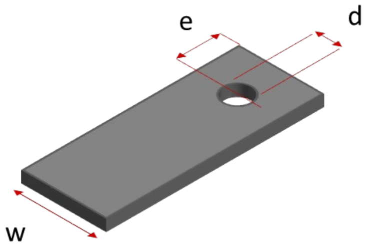


Figure 13: Geometrical parameters of typical test specimen, where 'e' is the distance between the hole and the end margin, 'w' is the width, and 'd' the diameter of the hole

4.6 Parameters in mechanical fastening

A wide range of geometric parameters must be considered in the design of mechanically fastened joints, in order to obtain a high level of integrity of the structure. The aerospace industry has to meet the highest safety requirements in operation as well as economic efficiency. In order to achieve safe aircraft structures, safe-life and damage tolerance philosophies need to be followed in the design phase and it is normal that a structure has a minimum life during which it is predicted that no catastrophic failure will occur. A benefit of nuts and bolts is their ease of assembly and disassembly, which is useful for allowing access to the interior of the structure for inspection and repair.

Mechanical joint designs for composite materials depend on the following main parameters:[17]

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[17] Clarke J L, 1996: 'Structural Design of Polymer Composites: EUROCOMP Design Code and Hand-book'. Chapman and Hall, London, 1996

- Selection of joining method (riveted or bolted joint)
- Joint configuration (single-lap, double-lap, etc.)
- Geometric parameters, particularly e/d and w/d ratios (Figure 13)
- Lay-up (stacking sequence)
- Clearance between fastener and hole
- Preload or initial clamping force

4.6.1 Joining method (bolts or rivets)

Rivets can be divided into solid and hollow types.[18] The hollow type is used when only single-sided access is available. One issue with the application of rivets is that the installation process involves the use of a closing force that may not be well controlled and this can result in wide variations of joint strength. In order to decrease the aerodynamic drag on external surfaces, countersunk rivets may be required. The countersunk angle should be as large as possible: 120° to 130°.[19]

Figure 14: Composite tailplane structure showing mechanical fasteners. Photo: Composites UK

As with rivets, bolts are also available for installation from one side (with a nut plate) as well as where both sides can be accessed. There is generally no thickness limitation when using bolts.

The use of non-permanent and permanent fasteners together is not recommended.[20] Since the permanent fasteners provide a better fit, the removable bolts will not pick up their share of the load until the permanent fasteners have deflected enough to take up the clearance between the removable fasteners and their holes (bolt hole clearance).

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[18] Phillips L N, 1989: 'Design with advanced composite materials'. The Design Council, (Springer-Verlag), London

[19] Matthews F L, 1999: 'Joining FRP with mechanical fasteners'. Presented in International Conference on Joining and Repair of Plastics and Composites, The Institution of Mechanical Engineers, London, UK / organized by the Aerospace Division of the Institution of Mechanical Engineers (IMechE)

[20] Niu M C Y, 1992: 'Composite airframe structures'. Hong Kong Conmilit Press Ltd

Despite the many benefits rivets can offer, one major disadvantage is the potential difficulty in removing rivets without damaging the parent material, particularly in composites.

4.6.2 Joint configuration

In general, the most efficient joints for composites are scarf and stepped lap joints, because they generate just a slight change in the load path.[20] Abrasive water jet and laser cutting operations offer the possibility to create these profiles. However, despite double lap and single lap joints being less efficient, they are widely used in aircraft structures because of their simplicity.

Single lap shear joints are commonly used in aircraft structures, particularly where the access is limited only to one side. [16] The main problem of single lap joints, however, is the eccentricity in the load path. [16] [20] The presence of a non-symmetric load leads to secondary bending which causes fastener rotation, non-uniformity of bearing stresses across the thickness of the laminate and, therefore, a reduction of strength compared to double lap joints (symmetric joints). As shown by Niu (1992) [20], to minimise the loss of strength when using single lap joints, multiple rows of fasteners are recommended in order to decrease bending caused by eccentric loading.

4.6.3 Geometric parameters

In some situations, geometric parameters (e/d and w/d ratios, see Figure 13) are chosen in order to encourage the less catastrophic type of failure, i.e. bearing failure. Bearing failure has less serious consequences compared with net-tension and shear-out, because the failure is gradual and progressive. Bearing failure can be obtained using large values of e/d and w/d ratios (e/d>3 and w/d>4) and, operating inside this range of values, failure load is independent of e/d and w/d. (See Figure 15).

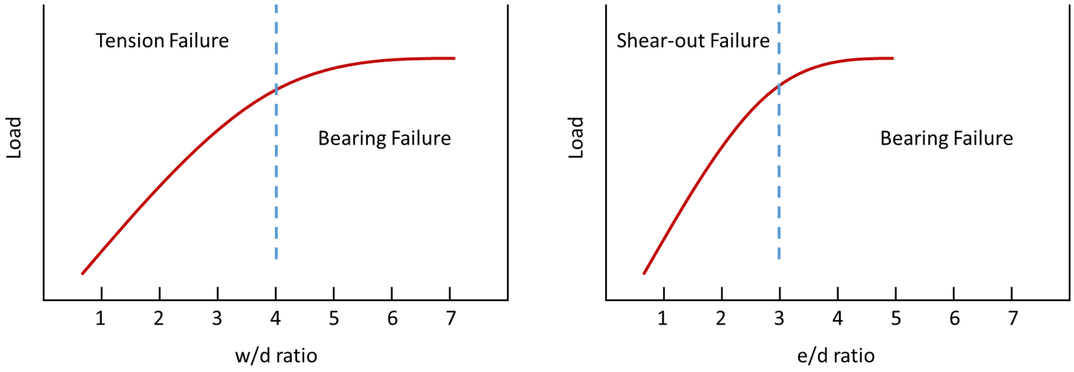

Figure 15: Transition between failure modes with variation in specimen width and end distance (Reproduced from Baker et al, 2004 [16])

High values of width (w) and end distance (e) produce joints that fail in bearing mode.[21] As the width is reduced the failure mode will eventually change to tension and the width at which the mode changes will depend on the lay-up. End distance generates an effect on shear out failure similar to the effect of width on tension failure. A reduction of the end distance value causes a possible change from bearing to shear failure. In general, the end distance should be equal to the width at which the failure mode changes from tension to bearing.

4.6.4 Lay-up (stacking sequence)

The lay-up of a composite material can affect the strength/failure of mechanically fastened joints. A joint in a unidirectional laminate fails by shear-out at very low loads when loaded parallel to the fibres.[21] If the laminate is loaded normal to the fibres, failure is in tension. As the proportion of ±45° material increases, the shear strength increases until bearing mode

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[21] Matthews F L, 1999: 'Joining FRP with mechanical fasteners'. Presented in International Conference on Joining and Repair of Plastics and Composites, The Institution of Mechanical Engineers, London, UK / organized by the Aerospace Division of the Institution of Mechanical Engineers (IMechE)

failure becomes predominant. Further increases in the proportion of ±45° material will possibly change the failure mode to tension, since the ±45° laminate has lower tensile strength.

The composite lay-up has an influence on the stiffness, failure load, bearing strength, and failure mode of mechanically fastened composite. Mechanically fastened (pins or bolts) joints in carbon/epoxy laminates with five different lay-ups (three quasi-isotropic and two orthotropic) were tested to failure in tension in a study by Park (2001).[22] The specimens were designed to fail in bearing failure mode (e/d and w/d = 5). It was observed that having 90° plies on the surface helps to improve the delamination strength for both quasi-isotropic and orthotropic lay-ups. From these results it appears that having 0° plies on the surface can decrease both the ultimate bearing strength and delamination strength.

A laminate fails by shear-out if it is dominated by 0° fibres with few 90° fibres.[20] Reinforcing plies at 90° to the load helps to prevent both shear-out and cleavage failures. To maximise joint strength, the optimum lay-up patterns are quasi-isotropic $(0/\pm45/90)_s$ and $(0/45/90/-45)_s$.

4.6.5 Fastener clearance

Another important effect to consider is the influence of the clearance between the hole and fastener on the performance of mechanical joints. Experimental studies have been carried out in order to determine the effects of bolt hole clearance on the stiffness and bearing strength of single lap composite joints with a single bolt. In a study by McCarthy, et al (2002)[23], composite lap joints were made of carbon/epoxy with a quasi-isotropic lay-up and aerospace grade titanium alloy fasteners having a nominal diameter of 8mm, and joints were loaded quasi-statically in tension. The important observations made were that there is a delay in the initial load take up, which is a consequence of increased clearance, and joint stiffness decreased with increasing clearance.

Composites structures do not gain any benefit from a large clearance. In fact, an interference fit is desired, although often impractical. An interference fit is a special case of zero, or slightly less than zero, clearance and is impractical as damage is typically caused during insertion of the fastener. The key advantages of an interference fit are:[24]

- Lower fastener deflection when joint is loaded
- Equal fastener load sharing
- Reduction of relative fastener flexibility that causes localised high bearing stresses
- Reduction or delay of hole degradation
- Lightning strike protection

Lightning strike protection deserves particular consideration when designing mechanically fastened joints in the aerospace industry. The high current resulting from a lightning strike can be dissipated easily by an aluminium airframe given its good electrical conductivity properties.[24] A carbon fibre reinforced composite structure is not equally conductive in all directions and thus it would behave as an anisotropic conductor (carbon fibres are 1000 times more electrically resistive than aluminium, and epoxy resin is one million times more resistive). In the case of lightning strike, the current must be dissipated from the fastener through the fibres perpendicular to the hole.[24] If an interference fit is not present, and therefore the fastener is not in a close contact with the sides of the hole, the instantaneous heat energy ionises the air in the gap and creates a plasma arc, severely damaging the structure. Therefore, the intimate contact of a fastener is the best option to allow dissipation of electrical current generated by a lightning strike.

Interference-fit fasteners can help to alleviate the reduction in strength caused by the presence of the fastened joint.[20]

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[22] Park H J, 2001: ‘Effect of stacking sequence and clamping force on the bearing strengths of mechanically fastened joints in composite laminates’. Composite Structures, Volume 53, Issue 2, pp.213-221

[23] McCarthy M A, Lawlor V P, Stanley W F and McCarthy C T, 2002: ‘Bolt-hole clearance effects and strength criteria in single bolt, single lap, composite joints’. Composites Science and Technology, Volume 62, Issues 10-11, pp.1415-143

[24] Parker R T, 2001: ‘Mechanical Fastener Selection’. ASM Handbook Volume 21, Pages 651-658

4.6.6 Preload or initial clamping force

Preload is a key parameter to take into consideration in order to obtain a reliable mechanical fastened joint system.[25] Providing the joint with sufficient preload ensures that the clamp force is not exceeded by the externally applied force. If the external force prevails over the preload, this leads to a separation of the joint faces (gap) and the risk that the fastener is subjected to bending forces and the joint faces to fretting, leading to failure of the fastener. A preload can significantly improve the bearing strength in addition to changing the failure mode from catastrophic to progressive. [22]

4.7 Environmental effects on mechanical joints

The study of the real behaviour of mechanically fastened composite joints is carried out by considering that the joint operates under a range of variable environmental conditions. Polymer matrix materials are significantly influenced by environmental conditions, and the effects of temperature (thermal effects) and moisture content (hygroscopic effects) are of particular concern. A combination of the environmental conditions of temperature and moisture content are often referred to as the hygrothermal effect. Increased temperature can cause polymers (in thermoplastic composites) to soften, compromising their ability to be used as structural materials.[26] In addition, variations in temperature and/or moisture content may cause physical alterations to the constituents (swelling or contraction), resulting in hygrothermal stresses and strains. For the reasons previously mentioned, environmental conditions may influence the failure modes and strength of composite joints and therefore it is important to include these considerations in the design of the joints.

Composites made of polymeric constituents often show viscoelastic behaviour at room temperature (i.e. creep, relaxation) and this behaviour is magnified when composites operate at elevated temperatures and/or in a humid environment. Viscoelastic effects in the polymer matrix have important consequences on composite properties, such as those governing the response to loading in the through-the-thickness (TTT) direction.[27] The effects of temperature, moisture and external load need to be considered for composites joined using bolts with an initial TTT preload.

4.8 Advantages and disadvantages of mechanical fastening

When mechanical joints are present in composite structures, a hole must be made to accommodate the fasteners, around which a stress concentration occurs. Additionally, if there are cut fibres around the hole, they can no longer transfer the load. The use of fastener holes results in micro and macro damage to the composite during joint fabrication. Consequently, strength degradation of the structure is inevitable.

In mechanical fastening, the fasteners themselves can be a significant source of weight increase. Particularly in weight-sensitive structures like aircraft, seeking ways of reducing the number of fasteners is a priority.[28]

In spite of its disadvantages, mechanical fastening is a well-proven joining method. It is the only feasible and economic method for joining highly loaded composite components in aircraft structures, while allowing relatively easy inspection of damage inside the material at the joint. The main advantages and disadvantages of mechanical joints are summarised in Table 3.[16] [21]

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[25] Bolt Science Limited, 2010: 'Terminology related to nuts and bolts'. Available from http://www.boltscience.com/pages/glossary.htm. [Accessed 24/10/19]

[26] Gibson R F, 2000: 'Modal vibration response measurements for characterization of composite materials and structures'. Compos Sci Tech 2000;60(15): 2769–80

[27] Shivakumar K N and Crews Jr JH, 1983: 'Bolt clamp-up relaxation in a graphite/epoxy laminate'. Long-term behavior of composites, symposium. ASTM STP 813. Williamsburg, pages 5–22

[28] Kweon J H, Junga J W, Kima T H, Choia J H and Kim D H, 2006: 'Failure of carbon composite-to-aluminum joints with combined mechanical fastening and adhesive bonding', Composite Structures, Volume 75, Issues 1-4, pp.192-198

Table 3: Advantages and disadvantages of mechanical joints in composites

Advantages	Disadvantages
Low initial risk (established technology)	Considerable stress concentration
Can be disassembled (maintenance or end of life)	Prone to fatigue cracking in component
No thickness limitations	Hole formation can damage composite
Simple joint configuration	Relatively poor bearing properties of composites
Simple manufacturing process	Prone to galvanic corrosion with some metallic fasteners
Simple inspection procedure	May require extensive shimming
Less environmentally sensitive	Sensitive to hole location and fit-up
Provides through-thickness reinforcement; not sensitive to peel stresses	Fastener over/under-tightening can cause failure
No major residual stress problem	Additional weight of fasteners
Easier inspection of damage	Can be expensive

The selection of appropriate geometries and materials is essential in order to achieve reliable composite structures. Design of bolted joints in composite materials is more complex than in metals due to the numerous combinations of composite materials and fibre patterns, complex 3D stress and strain distributions in the joints, and the existence of failure modes that may not exist in conventional metallic bolted joints. Another critical point is that failure of bolted joints in composites is not predicted either by perfectly elastic or perfectly plastic assumptions.[29]

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[29] O'Higgins R M, Padhi G S, McCarthy M A and McCarthy C T, 2004: 'Experimental and numerical study of the open-hole tensile strength of carbon/epoxy composites'. Mechanics of Composite Materials, Volume 40, Number 4, pp.269-278

5. ADHESIVE BONDING

5.1 Introduction

Adhesive bonding is probably the most versatile joining technology available to the engineer, and in the case of composites, it is often the most practical way to combine them with other materials such as metals and polymers. Indeed, composites themselves can be described as a product of adhesion between a resin (thermoplastic or thermoset) and the structural fibres within. However, in the vast majority of cases, adhesive bonding should be considered a pseudo-two dimensional, surface driven process where stresses and strains are transferred across an interface between two planes; the substrate (often referred to as the adherend) and the adhesive. Where the adhesive bond thickness is low, i.e. less than 100µm, the adhesive could almost be described as a single interphase region between two adherends. As the adhesive layer thickens, the adhesive becomes a component in its own right and the bond should be described as a sandwich of two adherends, two interphases and a layer of adhesive, with the bulk properties of the adhesive playing a larger role in the joint performance.

Such an emphasis on load transfer at the interface between the adhesive and the adherend has particular ramifications on composites in particular, due to the material properties of the supporting resin and the interlaminar adhesion between fibre layers in the z direction. The result of this is often seen by the failure zone moving out of the adhesive/interface region and into the composite material either in the resin rich surface, or between the laminar planes of the first and second ply, where the composite resin becomes the weakest region within the joint. Despite this unique aspect of composites, adhesives, due to their ability to spread loads over large areas with minimal impact on the underlying surface are often the joining process of choice when compared to mechanical attachment, where there is almost inevitable fibre damage and the creation of regions of high stress.

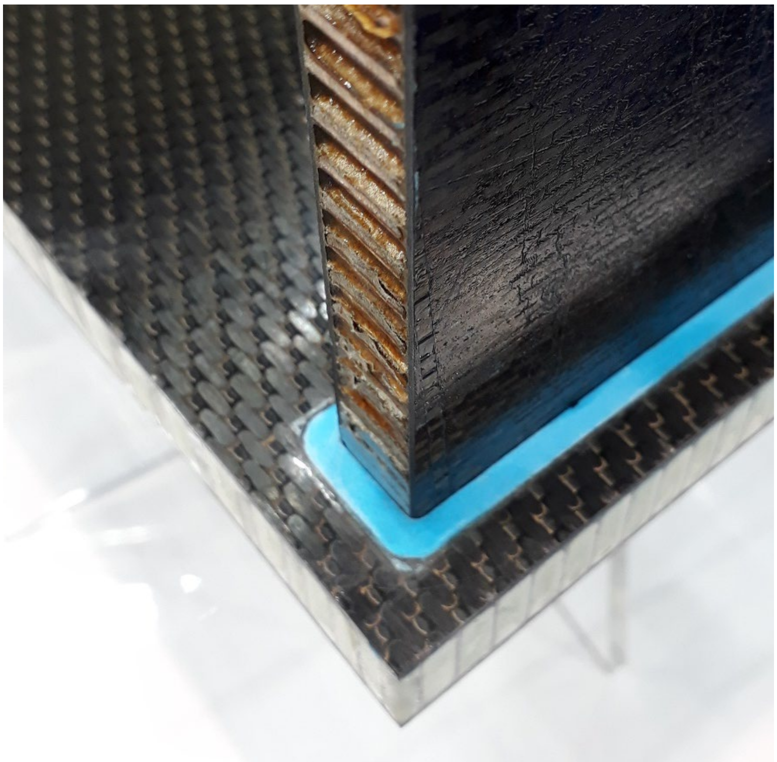

Figure 16: Sandwich panel butt joint. Photo: Composites UK

5.2 Adhesive processes and selection

5.2.1 Introduction

In simple terms, the sequence for making an adhesively bonded product is:

1. Design activities
2. Select materials

3. Design joint
4. Select adhesive
5. Manufacturing activities
6. Pre-treatment of the surfaces
7. Assemble
8. Cure
9. Final inspection

The bonding process requires consideration of all the following activities:

- Sourcing and storing adhesive system
- Adhesive application (metering, mixing, dispensing and control)
- Adherend preparation
- Assembly (order of assembly, environment, tooling)
- Cure (equipment and control)
- Inspection
- Repair
- Automation and robotics
- Factory layout
- Quality management
- Bonding co-ordination (equivalent to BS EN ISO 14731:2019, welding co-ordination)

A wide variety of adhesives are available from a range of adhesive manufacturers. It has been estimated that there are over 250,000 adhesive grades available from at least 1,000 suppliers world-wide. However, it is possible to simplify the choice by both understanding the basic types of adhesive and by applying selection principles with key deselecting questions.

5.2.2 Adhesive selection principles

Selection of an adhesive for a particular application may at first appear daunting. However, there are many sources of assistance, such as adhesive suppliers, expert consultants and computer-based selection systems. Since none of these sources can be comprehensive, there are some guiding principles which will help in any decision-making process.

The joint type, joint function, in-service conditions and manufacturing issues must all be considered. But by defining a few key performances or manufacturing requirements, this will quickly deselect most potential adhesive types. Key deselecting questions may consider one or more of the following:

- Maximum allowed cost
- Bond-line thickness or gap filling ability
- Maximum or minimum continuous temperature performance
- Mechanical performance required - for example, shear strength, extension
- Required open-time before cure
- Cure speed
- Tolerant of contaminated surfaces
- Required form of adhesive - for example, film, paste, liquid, one-part
- Special property required - for example, electrical, thermal, and optical
- Specific approval required - for example, fire rating, Mil-spec., FDA, medical
- Acceptable for site Health and Safety policies

5.3 Types of adhesive

5.3.1 Major classes of adhesive

Adhesives can be classified by several methods, none of them perfect, such as the way they set or cure (that is, transform from a wetting liquid to a load-bearing solid), the way they are used in assembly, their form prior to cure or by chemical type.

The strongest adhesives cure by chemical reaction, while lower strength adhesives typically harden by physical change, cooling from a melt or evaporation of a solvent. The major classes are described in Table 4 but more detail is given in subsequent sections for those which are most often used for composite materials.

Table 4: Summary of adhesive classes

Type	Description
Anaerobics	Anaerobic adhesives cure when in contact with metal, and the air is excluded (bolt/nut thread). They are often known as 'thread-locking compounds', being used to secure, seal and retain turned, threaded, or similarly close fitting parts, such as mechanical fasteners. They are based on synthetic acrylic resins. Such systems are not suitable for bonding composites only.
Cyanoacrylates	Cyanoacrylate adhesives cure through reaction with moisture held on the surface to be bonded. They need close fitting joints and usually solidify in seconds. Cyanoacrylates are suited to small plastic parts and to rubber and as such, are not well suited for bonding composite materials. They are a special type of acrylic resin.
Toughened Acrylics	Toughened acrylics, such as methyl methacrylate (MMA), are fast curing and offer high-strength and toughness. Both one-part and two-part systems are available. In some two-part systems, no mixing is required because the adhesive is applied to one substrate, the activator to the second substrate, and then the substrates joined. They tolerate minimal surface preparation and bond well to a wide range of materials including composites.
Epoxies	Epoxy adhesives consist of an epoxy resin plus a hardener. They allow great versatility in formulation since there are many resins and many different hardeners. Epoxy adhesives can be used to join most materials especially thermoset composites. Epoxies have good strength, do not produce volatiles during curing and have low shrinkage. However, they can have low peel strength and flexibility and may be brittle. Epoxy adhesives are available in one-part, two-part and film form, and produce extremely strong durable bonds with most materials. They can be selected to cure at room or elevated temperatures.
Polyurethanes	Polyurethane adhesives are chemically reactive formulations, which may be one-part or two-part systems and are usually fast curing. They provide strong impact-resistant joints and have better low-temperature strength than many other adhesive. Polyurethanes are useful for bonding glass fibre reinforced plastics (GFRP). The fast cure usually necessitates applying the adhesives by machine. They are often used with primers.
Silicones	Silicones are not very strong adhesives but are known for their flexibility and for their low and high temperature resistance. They are available in single or two-part forms. The latter function like the two-part epoxies, the former like the single-part polyurethanes. When the single-part adhesives cure they liberate either alcohol or acetic acid (the familiar smell of vinegar). Neutral cure silicones are also available which produce no by-products during curing. They are often used as bath and shower sealants. Their adhesion to surfaces is only fair but, like their flexibility, their durability is excellent. The two-part versions need a hardening agent to be mixed into the resin. Two single part forms are available - those which liberate acid on curing and those that do not. As might be anticipated, the two-part adhesive systems give a better cure in thick sections than do the single-part types.

Type	Description
Phenolics	Phenolics were the first adhesives for metals and have a long history of successful use for joining metal to metal and metal to wood. They require heat and pressure for the curing process and are not recommended for bonding modern composites.
Polyimides	Polyimides are available as liquids or films, but are expensive and difficult to handle. They are superior to most other adhesive types with regard to long term strength-retention at elevated temperatures.
Hot-melts	Hot-melts are generally based on thermoplastics or themoplastic-elastomers and are used for fast assembly of structures designed to be only lightly loaded.
Plastisols	Plastisols are modified PVC dispersions, which require heat to harden. The resultant joints are often resilient and tough but generally never used for composite bonding.
Rubbers	Rubber based adhesives are based on solutions of latexes and solidify through loss of the medium. They are not suitable for sustained loadings.
Polyvinyl Acetate (PVAs)	Vinyl acetate is the principal constituent of the PVA type emulsion adhesive. They are suited to bonding porous materials, such as paper or wood, and to general packaging work.
Pressure-sensitive adhesives	Pressure-sensitive adhesives are suitable for use as tapes and labels and, although they do not solidify, are often able to withstand adverse environments. This type of adhesive is not suitable for sustained loadings.

5.4 Types of adhesive for bonding composites - a closer look

5.4.1 Epoxy adhesives

This group of adhesives is widely used and is also one of the most diverse in terms of variants available. In the unhardened state, the chemical structure, from which the epoxy adhesive gets its name, is characterised by the ring-like shape of the epoxide group. All epoxy adhesives contain two or more of these groups per molecule of adhesive. Although they are all similar in this respect, the form in which they are available varies widely, from low-viscosity liquids to pastes or films. The wide variety of basic epoxy resins, in combination with over 70 different curing agents - ranging from simple amines to complex anhydrides - give the group its diversity.

Throughout all the variations, the mechanism of curing is always the same. The ring structure is broken by an active molecule - typically an amine - and the two monomers link. The constant repetition of this process hardens the adhesive by forming a polymeric network. This mechanism requires exact quantities of resin and hardener, hence the need for precise mix-ratios and the thorough mixing of resin and hardener in two-part systems. Without these, the polymer will not form correctly and often inferior properties will result - typically lower strength and reduced environmental resistance.

Single-part epoxy adhesives are also available, in liquid, paste or film form. The resin and catalytic hardener are pre-mixed but curing does not occur because the catalyst is in an inactive form at room temperature. It only becomes reactive towards the epoxide group as the temperature is raised, usually at a temperature in excess of 100°C. The higher the temperature, the faster the reaction becomes and hence shorter curing times are obtained. Cure of the two-part adhesives can also be accelerated by heat.

These materials have good strength and chemical resistance, do not produce volatiles during curing, and have low shrinkage. Therefore, they form extremely strong and durable bonds with most materials in well-designed joints. Development of toughened formulations (see later) has dramatically increased the use of these adhesives in many demanding applications.

The vast range of permutations open to epoxy formulation means that they are one of the most versatile adhesive families, able to bond to most adherends in most conditions for most environments and load conditions. Probably one of the few exceptions would be to bond the polyolefin family of materials i.e. polyethylene and polypropylene systems.

5.4.2 High temperature adhesives

Few adhesives are suitable for prolonged use at temperatures above 200°C. For specialist aerospace and electronic applications, in cases where brittle ceramic adhesives are not appropriate, then more exotic, synthetic polymers must be considered. Polyimide (PI) and bismaleimide (BMI) adhesives are the most established types in this class. They are available as liquids or films, but are relatively expensive and difficult to handle. However, they are superior to most other adhesive types with regard to long-term strength retention at elevated temperatures. It should be noted that these types of adhesives are only suitable for equivalent high performance composites where the resins are noted for their high thermal tolerance.

5.4.3 Polyurethane adhesives

These adhesives, often abbreviated to PU or PUR, which get their name from the chemical form of the hardened material, are another example of a two-part, chemically curing adhesive, and their reaction is very similar, in principle, to that of the epoxide.

The two components are mixed in exact proportions. Curing takes place by the reaction of alternating polymers containing alcohol or isocyanate groups, which form urethane linkages in the final polymer. They are available in a variety of forms, depending on the use required. The adhesive depends upon the isocyanate group for its high level of reactivity.

By comparison, the epoxide group is less energetic. As a consequence, the curing of two-part polyurethanes is much faster than that of most epoxy adhesives. Single-part formulations are available, which are partially polymerised and stable until cure is initiated by the action of absorbed atmospheric moisture. Their reaction rate is slower because it takes time to absorb the necessary water. Polyurethanes can be supplied as reactive chemicals, solvent solutions, pastes or hot melts.

They provide strong, resilient joints, which are impact resistant and have good low-temperature strength compared with many other adhesives. Polyurethanes find major uses in bonding of GFRP.

Figure 17: Application of two part methyl methacrylate (MMA) adhesive to GFRP panel. Photo: Lamplas

In a similar manner to the epoxy systems, PUs comprise a very large family, which can be tailored for a wide range of substrates and conditions. The main differences would be a much lower modulus and an intolerance of operating temperatures above 150°C. However, in contrast to limited high temperature performance, PUs have been shown to exhibit some of the best mechanical properties of all adhesives at cryogenic temperatures, even as low as liquid helium conditions (4°K).

5.4.4 Toughened acrylic adhesives

Toughened acrylics are relatively fast curing and offer high strength and toughness, plus more flexibility than common epoxies. They tolerate minimal surface preparation and bond well to a wide range of materials including metals and GFRP. They have sometimes been shown to be more susceptible to moisture attack (hydrolysis) and will rarely function above 200°C for any length of time.

5.5 Dispensing Adhesives

5.5.1 Introduction

Modern dispensing systems are designed to administer a range of adhesive types with various characteristics, for example:

- From thin liquids to pastes
- One- or multi-component products
- Adhesives applied in the form of tapes or films
- Cure times which vary from seconds to hours

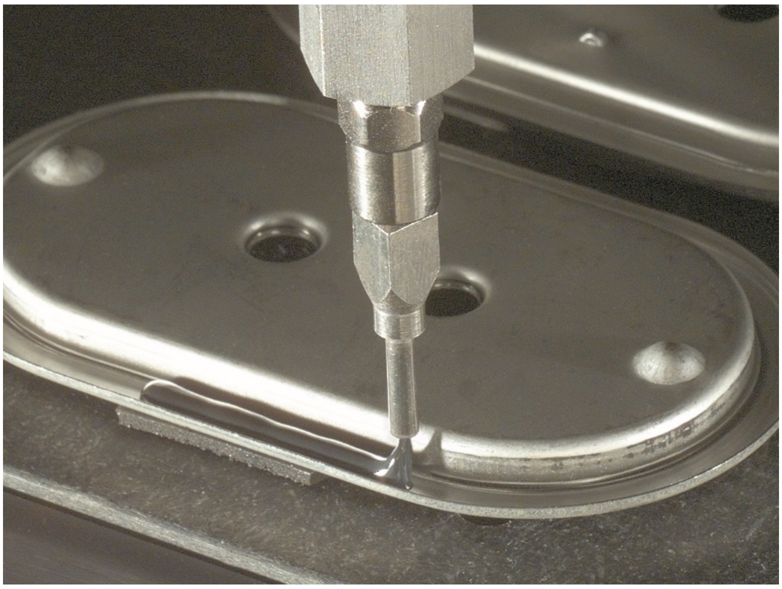

Figure 18: Robot dispensing adhesive. Photo: UK Flowtechnik

5.5.2 Principles of dispensing

Dispensing equipment is required to apply the adhesive:

- In the correct condition - for example, correct mix ratio
- At a consistent level of viscosity, with changes in temperature
- In the right place on the component
- At the correct production rate
- Cost-effectively, compared with other processes such as welding

The benefits of using dispensing equipment over manual application from a bottle, syringe or tube are:

- Cost-efficiency - dispensers ensure that no more adhesive than necessary is applied. Compared with manual application, as much as 50% can be saved on adhesive costs and this represents a quick return on investment

- Speed and adaptability - the bonding system (dispensing technology plus adhesive) is selected to meet with the manufacturing cycle-times of specific applications, whether operator-based or automatically controlled
- Precision - dispensers ensure that the adhesive is consistently and accurately dispensed for each cycle. They minimise the problem of trapped air, especially for mixed paste adhesives
- Health and Safety - dispensers ensure that operator exposure to adhesives is minimised

5.5.3 Basic dispensing principles

Dispensing involves the combination of several functions, depending on the method used. These include:

- Supply of energy to the bulk adhesive to move it through feed-pipes to a valve or pump, then to a dispensing nozzle
- Control of the valve or pump, to vary volume to be applied each cycle
- Control of the speed of movement between dispensing nozzle and component (either the component can be moved or the dispensing nozzle, depending on the application)

The major methods of dispensing are:

- Syringe or cartridge
- Pressure/time systems
- Pumps
- Hot melt adhesive dispensing guns
- Screen printing

Other methods include tape adhesive rollers, pin transfer (for microelectronic components) and spray.

5.5.4 Cartridge

In the majority of cases where a paste/liquid adhesive is being dispensed, the cartridge system is the most common. These may be single or double cylinders, with mechanical or air movement of the piston(s). Sizes typically range from 5ml to one litre. Figure 19 shows how applying pressure to the plungers allows equal measures of Part A (adhesive) and Part B (hardener) to be mixed automatically in the mixing nozzle. The mixed adhesive is then applied to the component as a single shot.

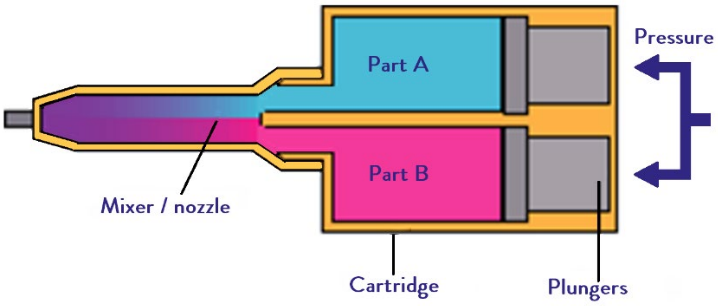

Figure 19: Principle behind a twin-cartridge dispenser

5.5.5 Film adhesives

After paste adhesives, film adhesives are probably the most commonly used adhesives for bonding composite materials. The benefits are obvious, i.e. they can be cut directly to the shape of the bond either manually with scissors or using automated processes such as lasers and kiss-cut tooling. The adhesive is contained within the film resulting in little or no excess adhesive at the edges of the joint after curing. However, certain disadvantages also exist which include:

- Higher cost
- Stringent storage conditions – normally require to be kept at sub-zero temperatures
- Requires high tolerance fit-up – little excess to fill uneven bond lines
- Potential absorption of water which can result in void formation during cure
- Normally requires heat to cure

5.6 Adhesive Joint Design

5.6.1 Introduction

Joint designs which are perfectly suited to other joining methods may be quite unsuitable for adhesives, and vice versa. The first part of this section gives a brief guide to key design considerations and provides details of various joint configurations used in adhesive bonding.

5.6.2 Strength of joints

Figure 20 shows the loading definitions used in this guide. In adhesive joints, load may be applied in shear, compression, tension, peel and/or cleavage. Load in peel and cleavage should be minimised by applying the principles of good joint design.

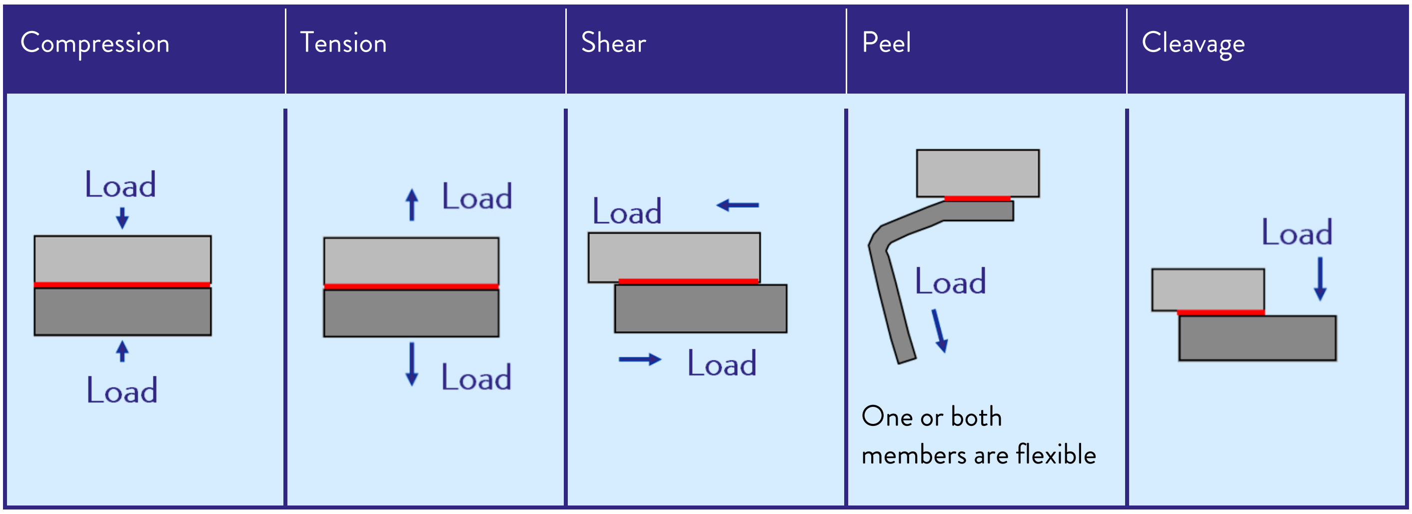

Figure 20: Bonded joint loading definitions

Adhesives should preferably be loaded in compression and shear, so as to minimise peel or cleavage forces in normal or accidental use. Even the best of the latest generation of toughened adhesives can carry loads roughly 100x greater in standard shear tests than they can in peel. While such tests are not directly comparable, they show that even small peel loads are particularly destructive.

In contrast, compression loads are readily borne. If the forces are compared, then the relative ability of a joint to withstand compression, shear and peel loading is of the order of 1000:100:1. With peel and cleavage designed out, the main consideration in joint strength is shear, as in the lap joint.

A typical lap joint is shown in Figure 21, along with a simple representation of the stress distribution along the bond line when load is applied along the long axis of the joint. When bonding thin sheet materials, the capability of a joint to take load in shear does not increase progressively with joint area because the load-carrying ability is limited by maximum stress at the leading and trailing edges of the joint. This applies much less to thick adherends. Only a very small portion of the load is carried by any part of the joint more than 15mm from the edge normal to the load, unless very flexible adhesives are used.

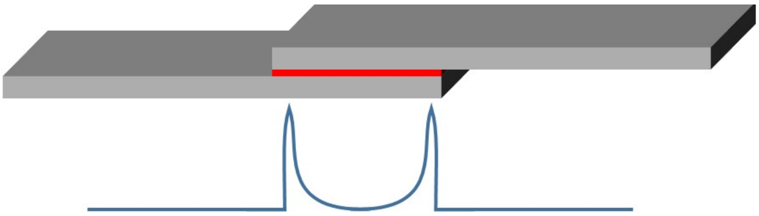

Figure 21: A typical lap joint with a typical representation of stress distribution along the bond line

The cohesive strength of the adhesive itself plays a key part in the overall strength of a bonded joint. Figure 22 shows the stress/strain relationships of a range of structural adhesive types.

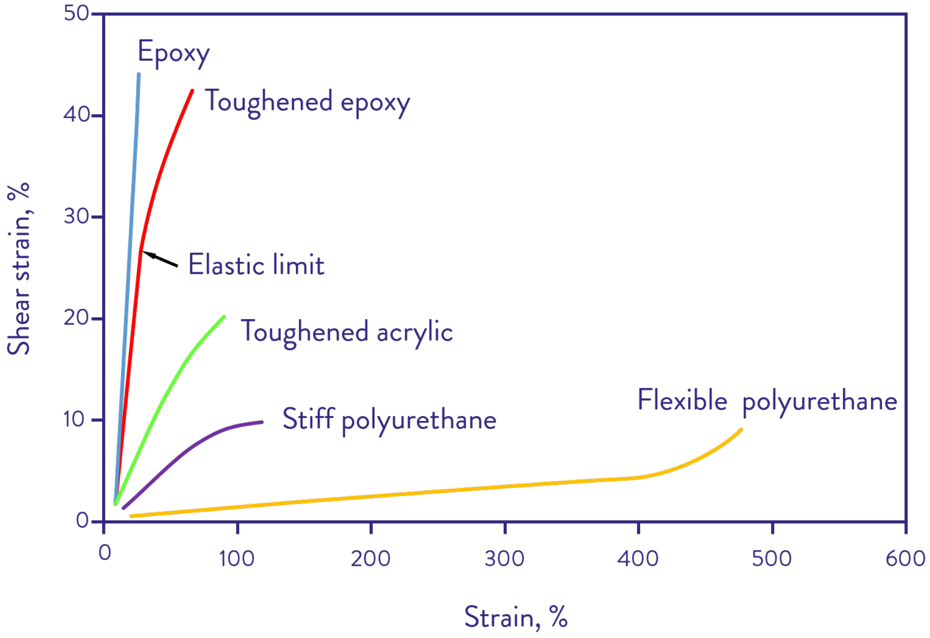

Figure 22: Typical stress/strain relationships for a range of structural adhesive types

5.6.3 Induced shock loads

A bonded assembly which is subjected to shock loading induced by accidental impact or as a performance requirement, can fail as a result of cleavage or peel forces, as illustrated in Figure 23.

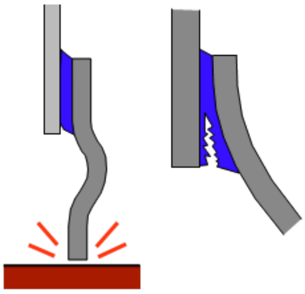

Figure 23: A bonded assembly subject to shock loading

5.6.4 Adhesive layer thickness and control

The maxim 'the thinner the adhesive line the better the joint' is not true in all cases. If applied too zealously by a literally minded bonder, it can lead to a joint starved of adhesive. Conversely, very thick bond lines, in particular when used with thin adherends (for example, 1 mm thick), can result in load offset, higher peak stresses and reduced strength of sheet bonding. High performance epoxy adhesives will perform best at bond-line thickness (BLTs) between 0.05 and 0.1 mm. At thinner bond-lines, there is insufficient adhesive to perform well in demanding situations such as preventing crack growth in fatigue loading.

In general different adhesive systems require different adhesive BLTs depending upon such factors as:

- Function/properties - for maximum peak strength an adhesive BLT may be small, i.e. less than 100 µm, but where the joint dimensions vary or impact resistance is required, the bond-line may be considerably larger, i.e. greater than 1 mm. For some adhesives such as epoxies and toughened acrylics, such a thickness range can be tolerated by a single system.
- Type of cure - for adhesives which cure through chemical reaction (e.g. epoxies, acrylics etc.) the bond-line thickness can be extremely small, whereas those which rely upon external factors, such as moisture curing polyurethanes or silicones, require a much larger BLT to enable a sufficiently large external surface area for effective moisture diffusion from the atmosphere.

5.6.5 Joint configurations

As has been discussed previously, adhesively bonded joints are particularly sensitive to the direction and type of loading and in view of this, there is often a compromise to be made in terms of joint complexity versus cost and performance.

Figure 24 shows a simple transition from a single lap joint through a stepped configuration to a scarf joint and ultimately a butt joint. The attraction of the lap joint is often driven by its ease of construction and low cost, whereas progression towards a scarf joint can be seen as one of increasing complexity and cost, although performance will be enhanced. In the case of composite joining, the stepped configuration can be quite attractive in that this can be incorporated into the initial fabrication process during lay-up. The butt joint should be avoided where possible due to the high cleavage loads that will develop upon any loading deviation from normal to the long axis.

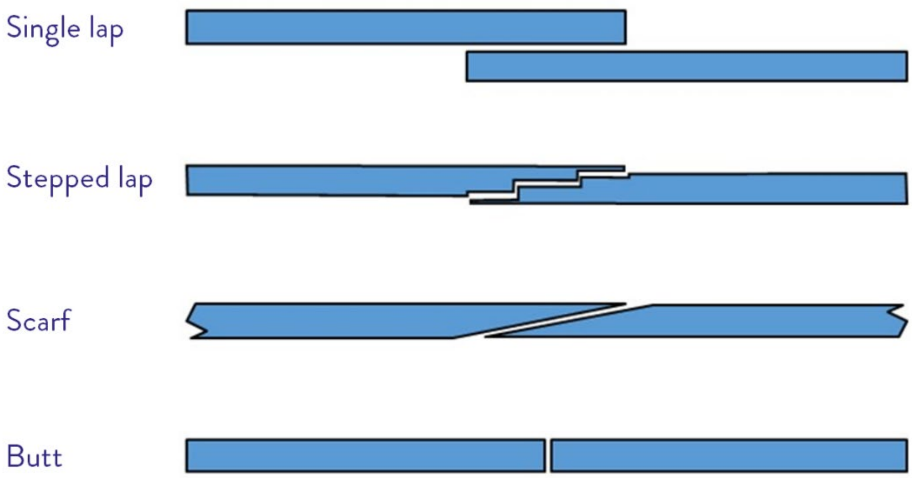

Figure 24: Various simple joint configurations

In lap joints, initial loading is carried in shear along the line of the joined components. As load is increased, the joint becomes progressively distorted and peel/cleavage forces come increasingly into play at the ends of the overlap as shown in Figure 25. In addition, tensile loads become significant across the joint. Failure occurs when:

- The adhesive fails - cohesion failure of the adhesive
- The adhesive fails at the surface of one of the joined parts - adhesion failure
- Parent material failure of the adherend, which in the case of composites is often termed inter-laminar failure

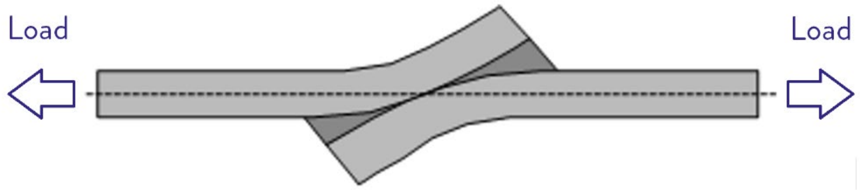

Figure 25: Distortion in joint overlap for single lap configuration.

5.6.6 Hybrid joints

Hybrid joints are those which combine two or more joining methods. Typically for composites these would be adhesives and fasteners of some type (rivets, bolts etc.).

The fasteners are useful in holding components together while the adhesive cures, obviating the need for additional temporary support, and where peel or cleavage forces cannot be avoided, they can be used to counteract such loads. Although the adhesive may well be secondary, it will still make a significant contribution to the overall performance, including stiffness of the structure.

5.6.7 Ease of assembly and joint design

Joint design must allow for cost-effective assembly. It is usually better to design joints so that the parts are pressed down on the adhesive rather than slid into position. Placement on, rather than sliding over, ensures that the adhesive is not pushed out of the joint detail. However, placement in any direction can result in trapped air, and appropriate precautions must be taken.

The design must also allow the adhesive to be applied in an appropriate pattern. Stripes and crosses are better than closed-loop patterns because they help avoid air entrapment when the components are brought together. Large bonded areas require careful and even dispensing of adhesive otherwise considerable pressure is required to squeeze out and spread the adhesive to a uniform thickness.

5.7 Joint Assembly (Jigs and Fixtures)

5.7.1 Introduction

In general, tooling or assembly equipment in the form of jigs and fixtures is required to achieve a high quality, reproducible adhesively bonded joint.

The function of assembly equipment is to locate and retain components together throughout the bonding process, i.e. adhesive application, structure assembly and adhesive cure. As the majority of adhesive systems exist as liquids or pastes before they cure or harden, jigs and fixtures are there to control the following key factors within an adhesively bonded joint:

- Bond-line thickness
- Joint alignment
- Fillet profile

These factors in turn have a direct impact on mechanical performance, cosmetic appearance, and assembly time.

Jigging and assembly aids for adhesively bonded systems can be broadly grouped into three categories:

- Internal agents, e.g. glass beads, wires or shims
- External agents, e.g. clamps, presses and plates
- Combination systems, e.g. riv-bonding (adhesive plus rivets)

5.7.2 Significance of bond-line control

Assembly tooling and related materials, in the context of adhesive bonding, can be defined as those systems/materials which retain components in a precise position and orientation during adhesive application and subsequent curing.

With the exception of pressure-sensitive adhesive systems (i.e. adhesive tapes) all adhesives must exist in a liquid or semi-liquid state prior to hardening/curing if an intimate bond is to be generated between the adhesive and the adherend.

The surface of the adherend needs to be fully wetted by the adhesive to maximise the bonding area and enable intimate physical and chemical bonding to take place. This can only be achieved with a liquid phase; however, unconstrained liquids have no direct load-bearing properties and tend to be displaced and flow away from an area under pressure, such as between two adherends. The rate and level of displacement depends on the pressure exerted and the viscosity of the adhesive. In addition, any joint that can move (e.g. through gravity because it is not lying flat) will tend to do so if it is not held in place prior to adhesive cure/hardening.

It is, therefore, necessary to use some sort of mechanical aid to locate and support the structure to be bonded until the adhesive in the structure has developed sufficient green strength or handling strength. Once this stage has been achieved, the structure can be self-supporting and tolerate removal of, or from, jigs and fixtures.

5.7.3 Pressure control vs bond-line control

Confusion often exists about how much pressure to apply to a joint during the adhesive curing process. In some instances, guidelines supplied by manufacturers indicate a certain minimum pressure; in others cases, no magnitude is indicated and this is often interpreted as 'as much pressure as possible'. However, as adhesives exist as liquids or partial liquids for a period of time prior to curing/hardening, care must be taken to control the application of pressure in order to avoid squeezing the entire adhesive from the joint. Nevertheless, pressure is required to hold the adherends together, to encourage wetting of the surface and, on some occasions, to address poor fit-up or tolerances by forcing the adherend surfaces together.

In order to address this issue, jigging or tooling is required to control the spacing between the adherends and therefore the BLT. This can be either internal, i.e. filler particles, glass beads, wires, carrier films, joint details, etc; or external, i.e. tooling, external shims, joint details, etc.

In summary, pressure is required for adhesively bonded joints but only when some type of BLT control can balance it.

5.7.4 The need for bond-line control

For virtually all adhesive systems, there exists an optimum BLT range for achieving the desired mechanical properties of high bond strength and resistance to creep.

If there is insufficient adhesive within the joint, it will be very weak and highly susceptible to defects such as bubbles or poorly wetted areas. If there is too much adhesive present, the joint may also be of lower strength since the properties of the bulk adhesive may dominate the structure due to inefficient load transfer from one adherend to the other. When the BLT is within the optimum range, load transfer is maximised and creep is minimised.

The ideal BLT range varies for different types of adhesive, for example: epoxy, 50-350μm; acrylic, 100-500μm; polyurethane, 500-5000μm. It is, therefore, very important that the user takes this into account during the design phase and then makes use of appropriate assembly aids during fabrication.

5.8 Adhesive Curing Requirements

5.8.1 Introduction

The majority of adhesives cure or harden by virtue of chemical reactions between reactive functional groups. The curing reaction can be initiated in a number of ways:

- Physically mixing the hardener and the base (in two-part adhesives), followed by a time-temperature curing regime, which can be at room temperature, e.g. two-part epoxies.
- Subjecting a pre-mixed hardener and base (often termed single-part heat curing) to a time-temperature programme where curing occurs, e.g. high temperature cure epoxies, acrylic cements.
- Exposing a liquid or paste to the atmosphere and allowing atmospheric moisture to cause a reaction - termed moisture-curing adhesives, e.g. silicones and cyanoacrylates ('super glues').
- Subjecting radiation curable adhesives (mixture of adhesive and radiation-sensitive initiator) to electromagnetic (visible, UV or IR) radiation.
- Depriving the liquid or paste adhesive of oxygen as in a thread-locking application - termed anaerobic adhesives (acrylic anaerobic thread-lockers).

To facilitate the full level of cure, specific conditions have to be applied depending not only upon the type of adhesive but also upon the structure and the materials to be bonded. Of specific relevance to composite bonding are the first three types described above i.e. room temperature, heat and moisture cure.

5.8.2 Room temperature curing

As the name suggests, this type of curing mechanism requires little external assistance. Room temperature (RT) is defined within the 15-30°C range. In general the curing rate is directly related to temperature, with higher temperatures causing higher rates of cure. As a rough rule of thumb the cure rate doubles every 10°C the temperature is raised and halves for every fall of 10°C. If the temperature falls too far below RT the rate may be so low that curing never reaches completion and the adhesive joint is compromised. At temperatures well above RT the rate may be so fast that either the adhesive fails to wet both surfaces completely when the joint is being assembled i.e. turning into a solid too quickly, or the adhesive suffers an exothermic reaction i.e. too much internal heat is generated, causing degradation or even burning. However, exothermic reactions only really occur when the adhesive is present in thick bond-lines or in a bulk form.

It is therefore important that the curing temperature is controlled carefully to ensure that the desired properties are achieved. For situations where the temperature may drop, it may be necessary to insulate the structure or use heating blankets. If the environment is too hot then cooling needs to be employed.

5.8.3 Moisture curing

Moisture curing adhesives rely upon the presence of atmospheric moisture to cure. If the environment is too dry, cure may not proceed to completion. This can be compensated for through the use of misting equipment to raise the local level of humidity.

5.8.4 Heat curing

A large number of structural adhesives rely upon heat to cure. Heating can be achieved either by placing the complete structure in an oven/autoclave or by enclosing the relevant area within a local heating cell employing heating blankets etc. The level and duration of heating normally depends upon the type of adhesive used but, in a similar fashion to RT curing adhesives, the more the temperature is raised, the more rapid the cure. Heat curing is a very common way to cure composites bonded by adhesives with the only limitation being the thermal stability of the composite resin.

Adhesives cured at temperatures above RT, will cause the joint to retain residual stress by virtue of the cross-linking reaction occurring at the elevated temperature, effectively locking the structure at that temperature. Such internal stresses can often be used to give benefit by countering applied external stresses whilst in service. Care should also be taken with respect to the rate at which the adhesive is taken to temperature, especially if the volumes of adhesive are fairly high, to avoid any type of exothermic reaction.

5.9 Advantages and disadvantages of adhesive bonding

Adhesives can provide many benefits over other types of joining technology and composites are no exception. However, it is important to provide a balanced view where disadvantages, both real and perceived are described in Table 5.

Table 5: Advantages and disadvantages of adhesively bonded joints in composites

Advantages	Disadvantages
Provision of large, stress-bearing area – especially relevant for composites as explained in the previous section.	Some type of surface preparation will be required – composite surface preparation will either require some type of cleaning, followed by abrasion/peel-ply removal and then a subsequent cleaning stage prior to bonding.
Excellent fatigue strength.	Significant cure-times may be required.
Good shock absorption – this property is dependent upon the type of adhesive selected and the design of the joint.	Heat and pressure may be needed to cure an adhesive.
Reduced galvanic corrosion – of particular importance where carbon fibre systems require to be joined to metals such as aluminium and steel.	Jigs and fixtures may be required to locate components whilst the adhesive cures.
No need to have access to far-side of adherend to make joint.	Rigid process control is required to obtain consistent results.
Bonding is possible on dissimilar materials.	Conventional non-destructive inspection of bonded joints is difficult.

Provision of smooth contours and sections around joint areas.	Adhesives have a finite shelf-life prior to curing and may require special storage conditions before use.
Sealing properties.	Adhesives have poor resistance to peel and cleavage stresses in relation to shear and tension loading – ideally the best loading direction is in compression.
Weight reduction – in contrast to other joining technologies where fasteners are required and additional composite is required to maintain performance around holes, the only added mass is that of the adhesive which in not normally significant.	

6. WELDING (FUSION BONDING)

6.1 Introduction

One of the advantages of thermoplastic over thermoset composites is that they can be melted and reshaped. As such, they can be joined together by welding, also known as fusion bonding. This section, therefore, is limited to thermoplastic matrix composites. Thermoset composites can be joined using a form of welding, where a thermoplastic interlayer is melted and creates a joint between the thermoset parts, but this process has more in common with adhesive bonding, as there is no comparable molecular diffusion or intermixing at the interface between the thermoset and thermoplastic.

Many composite welding techniques have been developed over the past decades. They typically fall into three categories depending on the nature of the energy source used to provide the heat to melt the thermoplastic:

- Electromagnetic heating
- Mechanical heating
- Externally heated techniques

The main composite welding techniques are described in the following paragraphs. It should be noted that no single welding technology can be applied to all situations as they present advantages and drawbacks that can be more or less suitable to a particular application, depending on its specific requirements. Table 6 includes the different welding techniques presented here along with joint requirements and limitations.

Table 6: Joint requirements for electromagnetic heating welding techniques

Welding Techniques		Joint Design	Implant /Additive	Matrix Colour	Reinforcement Type
Electromagnetic	Induction	Complex	Only if reinforcement is non-electrically conductive	Any	Continuous carbon fibres, or conducting implant
	Microwave	Complex	Microwave-susceptible implant	Any	Any
	Laser	Limited complexity (top component thickness)	Absorbent additive (if bottom component transparent)	Top (transparent) vs. Bottom (absorbent)	Transparency limitation in top component
	Infrared	Limited complexity (no preassembly possible)	No	Clear (non-absorbent) plastics preferred	Opacity limitation in both components
Mechanical	Vibration	Linear / only one direction of curvature	No	Any	Short fibres preferred
	Ultrasonic	Limited complexity	Interfacial projection / roughening	Any	Short fibres preferred

Welding Techniques		Joint Design	Implant /Additive	Matrix Colour	Reinforcement Type
External	Hot Plate	Linear	No	Any	Short fibres preferred
	Resistive implant	Limited complexity	Yes	Any	Any

6.2 Electromagnetic Heating

6.2.1 Resistive Implant (Resistance) Welding

Resistive implant welding, also known as resistance welding, involves placing an electrically conductive element (insert or implant) between the two parts to be joined and then resistively heating the insert by passing a high electric current through it. As the implant heats due to Joule (or ohmic) loss, the surrounding thermoplastic softens, melts and with the aid of applied pressure, forms a welded joint upon cooling, see Figure 26.

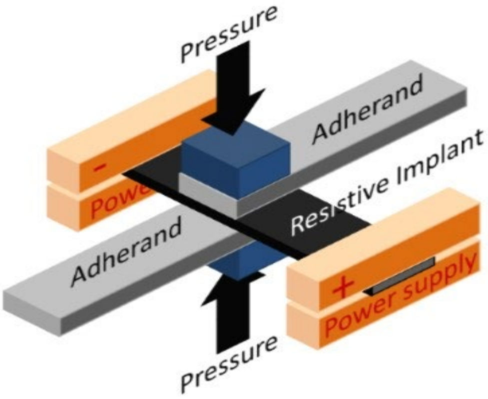

Figure 26: Resistive implant welding process schematic

The inserts are typically metallic (e.g., nickel/chromium, steel) in a wire, braid or mesh form, or unidirectional carbon fibre strips. An example of a composite part joined by resistive implant welding is provided in Figure 27. In a braid, UD tape or woven fabric form, inserts are typically interwoven with monofilaments of the polymer being welded. The electric current is generally DC or low frequency AC. The power can also be applied in the form of intense pulses, in which case the technique is called impulsive resistance welding, which requires less energy to melt the matrix. Good thermal insulation and a correct amount of input energy can enhance the weld quality while reducing the welding time. [30]

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[30] da Costa A P, Botelho E C, Costa L M, Narita N E and Tarpani J R, 2012: 'A Review of Welding Technologies for Thermoplastic Composites'. Aerospace Applications. J. Aerosp. Technol. Manag., Vol. 4, pp 255-265. Doi: 10.5028/jatm.2012.04033912.

Figure 27: Resistive implant welded Twintex® (glass/polypropylene). Copyright © 2020 TWI Ltd reproduced with permission

Resistive implant welding is a simple technique which can be applied to almost any thermoplastic, with the exception of parts where heavy carbon loading or non-insulated metal components can cause current leakage from the joint area. Resistive implant welding is particularly well suited to joining carbon fibre-reinforced composite materials, as a single ply of the composite material can be used as the implant. In this case, an electric current is passed down the carbon fibre ply implant, which is heated due to Joule losses. The main advantages of resistive implant welding are its rapidity (typically 1 to 4 minutes to form a weld) and its potential application to large structures, such as the marine application shown in Figure 28.

Figure 28: Resistive-implant welded assault craft bow. Copyright © 2020 TWI Ltd reproduced with permission

6.2.2 Induction Welding

Induction welding describes welding techniques where heating is generated by an induction field (Figure 29). Two common mechanisms by which heat can be generated by an induction field are:

- Eddy current heating: energy dissipation due to Joule heating, also known as ohmic heating (typical for carbon fibres)
- Dielectric hysteresis heating: energy dissipation due to magnetic hysteresis (typical for ferromagnetic materials, such as a metallic mesh implant)

The heat generation by Joule effect is described by:

$$P \propto I^2 R$$

Where the heating power (P) is proportional to the product of induced current (I) squared and resistance (R). Since thermoplastics are typically poor electrical conductors, an electrically conducting material must be present at the joint interface in order to sustain the induced eddy currents. If the composite reinforcement is not electrically conductive (e.g., glass fibres), then an implant is required.

In induction welding by eddy currents, a work coil connected to a high frequency power supply is placed in close proximity to the joint. As a high frequency electric current passes through the coil, a dynamic magnetic field is generated whose flux couples with the conductive fibres or the implant. As a result, an electric current is induced, thereby heating up the conducting material, which in turns melts the surrounding thermoplastic. Pressure applied to the joint helps ensure that molten thermoplastic forms a strong bond (by enhancing the intimate contact between the two surfaces being joined and facilitating polymer chain entanglement).

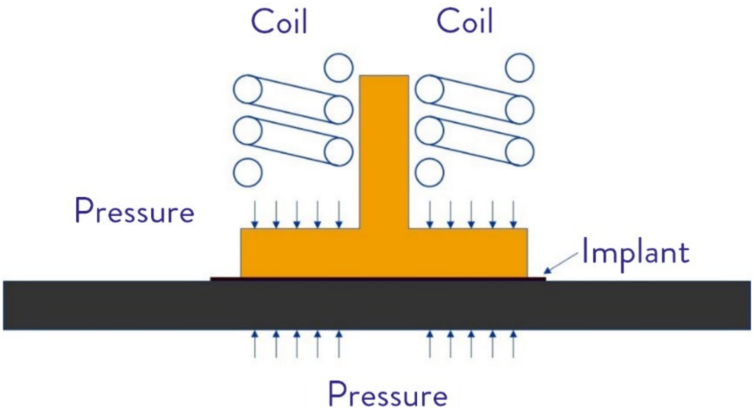


Figure 29: Induction welding process schematic; T-stiffener welded to a skin

If an implant, typically a metal wire mesh, is used, it remains in the joint at the end of the weld cycle. The implant has, therefore, a potentially detrimental effect on the structural properties of the weld, especially if the structure is exposed to a corrosive or wet environment. It may also cause issues with subsequent non-destructive testing as the metal and composite may behave very differently in the selected testing technique. The mesh comes in a variety of sizes, with a typical thickness of approximately 0.5 mm.

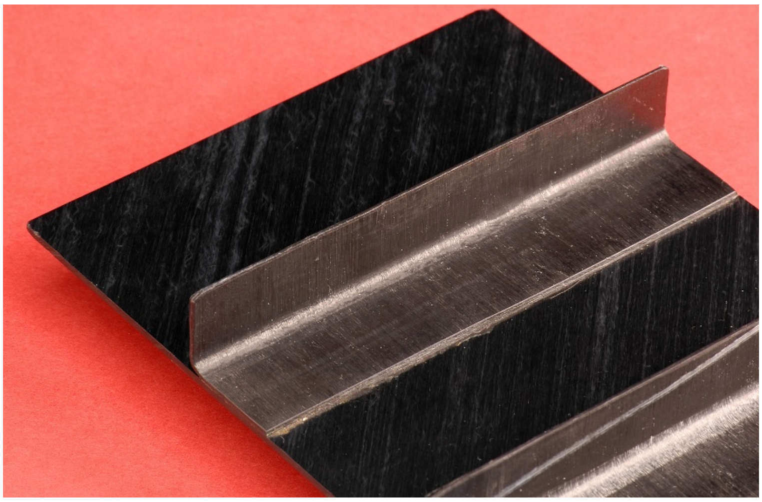


Figure 30: Induction welded stiffened skin (Carbon/PEEK). Copyright © 2020 TWI Ltd reproduced with permission

6.2.3 Microwave Welding

Most thermoplastics do not experience a temperature rise when irradiated with microwaves. Microwave welding therefore requires the use of a microwave-susceptible implant at the joint interface, or joint line. As the joint, typically maintained under mechanical pressure, is subjected to microwave energy, the implant heats up and melts the surrounding plastic material to form a weld upon cooling. Implants can be carbon-impregnated tapes, ferrite-loaded materials or conducting polymers. Metals will arc in the presence of microwave radiation, so it is not recommended that this welding technique be used for welding metal/polymer combinations. Glass or Kevlar fibre reinforced thermoplastics can be microwave welded. The process may be suitable for thermoplastics to themselves or to thermosets using a suitable interlayer.

Despite the availability of commercial microwave ovens (Figure 31), microwave welding is still a relatively immature joining technology for composites.

An advantage of microwave welding is its ability to irradiate the entire component and consequently produce complex three-dimensional joints. Welds are typically formed in less than one minute. [30]

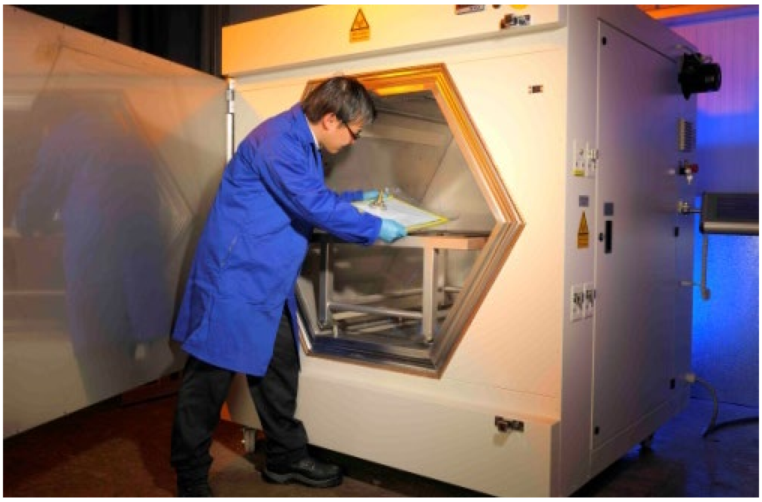
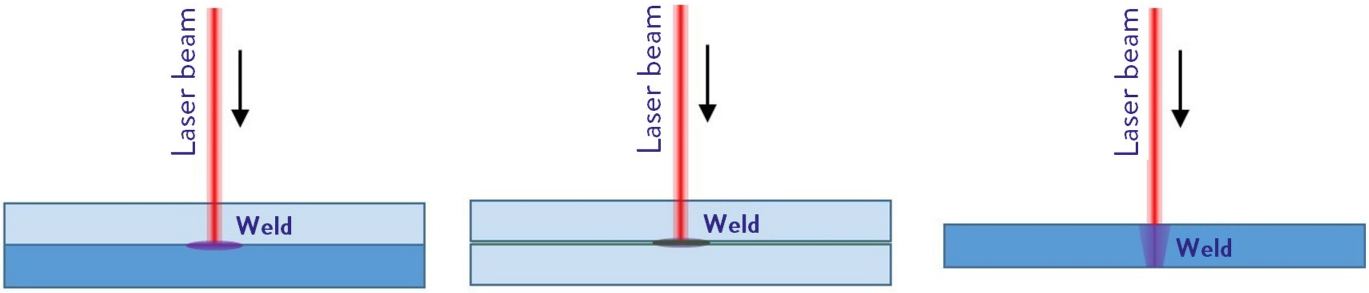


Figure 31: Commercial microwave oven designed for processing composites. Copyright © 2020 TWI Ltd reproduced with permission

6.2.4 Laser Welding

Laser welding, also known as laser beam welding (LBW), of thermoplastics involves the use of an intense radiation beam, usually in the infrared or near visible regions of the electromagnetic spectrum, which is absorbed at the joint interface, thereby causing the thermoplastic to heat, melt and form a weld. Like with microwave and induction welding, the application of pressure on the joint during the process is essential to ensure a strong weld be formed.

Laser welding can be used to join thermoplastic composites provided that one of the materials (referred to as top material for clarity) is sufficiently transparent to laser radiation and the other (the bottom material) is absorbent enough for the welding to take place (Figure 32a) or, if the bottom material is not absorbent, an absorbent interfacial additive can be used (Figure 32b). Otherwise only butt joints can be laser welded (Figure 32c). [30]



(a) Transmission with absorbing base layer

(b) Transmission with absorbing dye at interface

(c) Butt joint where both components are radiation-absorbent

Figure 32: Schematic of laser welding

CO_2 lasers can be used to weld films of thermoplastic in a lap joint configuration very effectively. Welding speeds can be many tens of metres per minute, making the process ideal for high volume production. By careful control of the laser beam profile it is also possible to make a weld and cut at the same time in an operation called cut and seal.

Welds in thermoplastics of over 1mm thickness can be achieved using shorter wavelength (Nd:YAG and diode) lasers. With such lasers, through-transmission laser welding can be used, where the energy from the beam is transmitted through the top component and absorbed at the interface by the bottom component[31] or by an infrared absorbent dye placed at the interface. The presence of reinforcing fibre in a polymer composite can also limit the passage of light due to increased scattering. This may limit the thickness of a composite that can be welded.

An alternate approach is to irradiate the two joining surfaces with a laser sufficiently to melt the thermoplastic on the surface. The two parts are then brought together and held under pressure until the weld has formed. Although suitable for joining small parts, the need to quickly manoeuvre large composite structures into the precise location required for joining makes this an impractical solution for large, heavy structures.

6.2.5 Infrared Welding

Infrared welding is another non-contact technique for joining thermoplastic composites. In this process, infrared lamps are used to heat the joint surfaces directly. Once the surfaces are heated, the lamps are removed and the surfaces brought together to make a weld, in a similar manner to hot plate welding (Section 6.4.1). Unlike hot plate welding, it is a non-contact heating method with no possibility of material sticking to the heat source.

The benefits of infrared welding are numerous:

- It reduces the risk of weld contamination from charred particles of polymer or the addition of an implant.
- The heating step is fast (typically 5 seconds).
- The resulting joints have a high structural reliability.

On the other hand, the technique presents a number of shortcomings:

- Pre-assembly of parts prior to welding is not possible.
- The presence of colorants or pigments may reduce the quality of the end-product through overheating and surface degradation, especially with dark polymers.

6.3 Mechanical Heating

As with processes involving mechanical movement, there is the potential for fibre damage at the interface. This has to be taken into account during the selection of the joint design and type of reinforcement.

6.3.1 Friction Welding

Friction welding is a process in which the surfaces to be joined are pushed together and then vibrated (or rubbed) to generate heat. When the heat has caused sufficient melting, the vibration is stopped and the components are aligned and allowed to cool. This technique is particularly useful for joining linear objects that are too large for ultrasonic welding or where hotplate welding would take too long.

Welding of thermoplastic parts by frictional heating is usually achieved by three main processes:

- Linear friction welding (also known as vibration welding)
- Rotary friction welding (also known as spin welding)
- Orbital welding

These processes are suited to composite materials where short, discontinuous fibres form the reinforcement of the material. However, linear friction welding has also recently been demonstrated on continuous fibre-reinforced PEEK (polyetheretherketone).

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[31] Vacogne C and Wise R, 2011: 'Joining of high performance carbon fibre/PEEK composites'. Science and Technology of Welding and Joining, Vol. 16, pp 369-376. ISSN 1362-1718. Doi: 10.1179/1362171811Y.0000000027.

Linear friction welding of thermoplastics involves the rubbing together of the weld interface in a linear motion. Typically, the frequency of vibration is 100-200 Hz at an amplitude of 1-4 mm. Component design needs to incorporate one plane that allows for vibration movement during the welding process, thereby excluding complex welds (e.g., components with more than one direction of curvature).

6.3.2 Ultrasonic Welding

Ultrasonic welding is a process in which high frequencies are used, typically ranging from 15 to 70 kHz.[30] This process generally requires a projection at the interface to direct the ultrasonic energy and initiate the material melt flow. This type of joint geometry is hard to achieve in a continuous fibre thermoplastic composite fabrication, making the process difficult to use for welding these materials. An alternative to be considered would be the use of a surface roughening treatment on the component faces to be joined, to direct the energy for welding.

Successful welding relies upon careful selection of tooling, welding horn (device used to deliver ultrasonic energy), machine design, welding parameters and joint design. This process has predominately found applications in the assembly of mass produced injection moulded plastic goods where the short cycle times (typically 1-2 seconds) are ideal for high component throughput. Although the size of the horn used in ultrasonic welding is limited to around 250 mm, it may be possible to consider multiple ultrasonic welding systems to cover larger components.

Amorphous plastics readily transmit the ultrasonic energy due to their higher modulus of elasticity compared with typical semi-crystalline plastics. This means that a weld can be made through a greater thickness of amorphous plastic, and using less energy than is required with typical semi-crystalline materials.

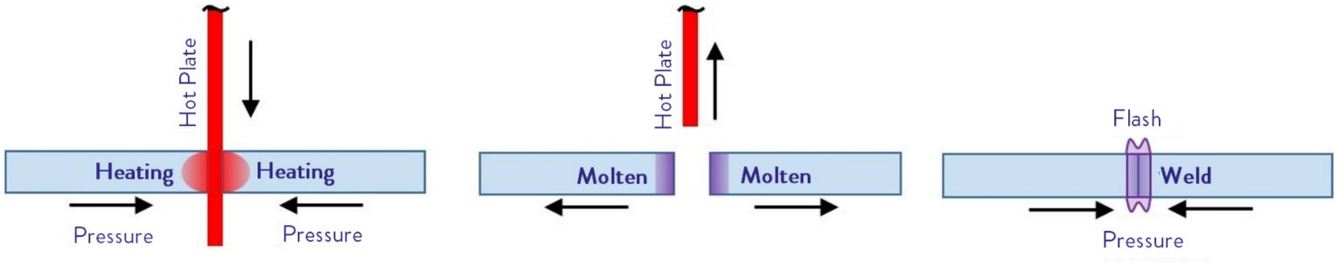
6.4 Thermal Techniques

6.4.1 Hot Plate Welding

Hot plate welding, also known as heated tool welding, is one of the most popular methods for joining thermoplastics because of its simplicity, reliability and cost effectiveness.

The parts to be joined are held in fixtures that press them against a heated tool. The process cannot, therefore, be applied to pre-assembled parts. Heating takes place in two stages:

- In the first stage, the heated tool melts the thermoplastic surfaces and material is displaced against the tool so that a smooth surface is obtained (Figure 33a). Mechanical stops in the equipment, or a reduction in pressure, prevent further displacement but the parts continue to be heated by the tool until they are softened some distance away from it.
- In the second stage, the fixtures then open, the heated tool is withdrawn, and the fixtures force the parts together (Figure 33b, c). Mechanical stops in the equipment or a pressure controller regulate the displacement (or flash) of the parts during this stage of the welding process. The parts are held together until the weld is cool.



(a) Hot plate placed between joining parts, pressure applied to heat the interface

(b) Hot plate removed ready for forging

(c) Forging, with flash formation and a finished weld.

Figure 33: Schematic of hot plate welding

The surface of the hot plate is sometimes coated with polytetrafluoroethylene (PTFE) to prevent the adherence of molten thermoplastic. It is important that the temperature across the surface of the hot plate does not vary by more than approximately ±5 °C in order to produce welds of consistent quality. Weld pressure may be applied pneumatically or hydraulically, depending on the size of the joint area and the equipment configuration. While small parts demand between five and 60 seconds to be welded, large parts take at least 30 minutes to guarantee a good connection. Risk of surface contamination is one of the main drawbacks of this technique.

7. SURFACE PREPARATION & PRE-TREATMENT

7.1 Introduction

Synthetic adhesives have been used successfully for many years in many industry sectors and it is generally accepted that to obtain the optimum performance from an adhesive joint, some level of pre-treatment is required. The type of pre-treatment is often a compromise between the best surface preparation, economics of component manufacture and health and safety issues.

The benefits of using appropriate surface pre-treatments are:

- Enhanced mechanical performance of joint
- Improved joint durability in aggressive environments
- Increased service-life of component
- Ability to bond difficult adherends, e.g. polyolefins and PEEK

7.2 Purpose of pre-treatment

Pre-treatment is carried out to achieve one or more of the following:

- To ensure consistency of the bond surface and thereby facilitate a high level of quality assurance
- To remove completely, or to prevent formation of, what are often referred to as weak boundary layers. Examples of weak boundary layers include weakly attached material to the surface after a blasting or abrasion process, plasticisers which have migrated to the surface of polymers, mould release agents from tooling surfaces or from within peel-ply. Other surface contaminants include dust, dirt, grease, oils and even finger marks!
- To form an effective bond, intimate molecular contact between adhesive and adherend is required. The correct surface pre-treatment will optimise this degree of contact, which may be brought about by chemical modification of the adherend surface.
- To produce a specific adherend surface topography, thereby altering the surface profile, and possibly increasing the bondable surface area, that is, to roughen the surface

It is often necessary to protect the adherend surfaces before bonding as a prepared surface is highly reactive not only towards adhesives but also to atmospheric contaminants. To preserve the integrity of the adherend surface it is usually necessary to bond the surface within a few hours of treatment, or to coat it with a primer which is compatible with the adhesive to be applied later.

The full mechanism behind adhesion is complex and can be accounted for via a number of combined mechanisms including mechanical interlocking, Van der Waal's attraction, diffusion theory, adsorption theory etc. The treatments described in this section enable some or all of the adhesion processes to be enhanced but there is no single process that either enhances them all to the same degree or promotes any single process. Clearly mechanical abrasion and related pre-treatments create an increased amount of mechanical interlocking but the actual act of surface disruption and ablation may also cause new chemical species to be generated and fresh surface to be exposed.

7.3 Main types of composite pre-treatment

There are a wide range of surface treatments available. Many adhesives or adherend suppliers give advice on how to prepare a surface prior to bonding. Best practice is covered in ISO 17212:2012.[32] Techniques can be classified into five groups, according to the nature of treatment:

- Cleaning/Degreasing: Removal of loose solids can be accomplished with a clean brush or blast of clean, dry air. Organic solvent or alkaline, aqueous solution removes organic materials such as grease, oil and wax from adherend surfaces. This can be accomplished by wiping, dipping or spraying.
- Surface Roughening: Techniques where abrasive materials are employed to remove unwanted layers and generate a roughened surface texture.
- Chemical Treatments: Immersion of the adherend in an active chemical solution which has the power to etch or dissolve a part of the adherend surface or change it in such a way that the treated surface becomes chemically active.
- Physical / Energetic Treatments: This includes methods where the adherend surface is cleaned and chemically modified by exposure to excited charges or species. Techniques such as corona discharge, plasma, flame or exposure to ultraviolet/ozone are examples in this group.
- Primers: These are chemical reagents which can be applied to adhered surfaces; Primer application is often simpler than chemical or physical methods, applied by dipping, brush or spray.

In general, the above types of surface pre-treatment can be divided into three major categories: mechanical; chemical; energetic.

7.4 Overview of mechanical, chemical and energetic pre-treatment

Selection of surface pre-treatment should be appropriate to performance requirements and be compatible with manufacturing procedures, cost, durability and health and safety. Pre-treatment facilities can include equipment, chemicals and consumables.

Key surface features (resulting from pre-treatment) which should be kept in mind are wettability, roughness, consistency, stability, contamination, uniformity and adhesive compatibility.

7.5 Mechanical pre-treatment

Mechanical abrasion is the most widely applicable surface preparation technique, being suitable for most materials including composites. It can include:

- Abrasion (disk, wheel, pad)
- Grit-blast
- Cryo-blast
- Soda-blast
- Peel ply

Mechanical abrasion will remove weak boundary layers. It will also change the surface topography of the adherend, increasing the bondable surface area on a microscale. The process will enhance the adhesive's ability to 'wet' (when the adhesive readily and completely covers) the surface of the adherend. Mechanical abrasion can lead to better adhesion by providing mechanical interlocking between the adhesive and adherend.

The simplest form of abrasion uses silicon carbide paper to abrade/polish surfaces. This method may be carried out dry or in conjunction with a suitable solvent. The quality of the adherend surface obtained with silicon carbide depends upon the grit size and whether the operation is performed manually or mechanically. It is necessary to monitor carefully the abrasion

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[32] ISO 17212:2012 'Structural adhesives. Guidelines for the surface preparation of metals and plastics prior to adhesive bonding'

since, if the process is carried out for too long, surface debris initially removed can be re-deposited. For composites, it is important to note that mechanical abrasion may cause fibre damage and impair performance of the joint.

Blasting is another form of mechanical abrasion and includes alumina grit blasting, cryo-blast and soda-blast. The use of alumina is one of the commonest approaches and can be used effectively on composites if applied carefully. Over-blasting will remove all of the surface resin but can result in fibre damage and potential subsurface cracking if appropriate controls are not in place. Cryo-blast and soda-blast are also used for preparing composite adherends, being less aggressive than alumina grit. Cryo-blast utilises solid carbon dioxide pellets and relies on thermal shock to remove loosely bound surface material including paints, whereas soda-blast uses sodium bicarbonate particles which are much softer and less likely to cause subsurface damage.

For peel-ply surface preparation, a method used almost exclusively for composites, the peel-ply fabric is used as the final layer in the lay-up process. During the cure cycle, the resin matrix flows and penetrates the fabric creating a sacrificial top layer/coating on the composite. When the composite is required for bonding, the fabric is peeled off, fracturing the resin between the fabric and the first layer of fibre reinforcement, producing a clean, roughened surface to which the adhesive can be applied. The surface morphology obtained is dependent on the nature of fabric and type of weave used. However, the peel-ply fabric is often pre-treated with release chemicals to make it easier to peel off. These chemicals then need to be removed from the surface of the composite and this is most commonly done through some type of mechanical process such as abrasion or blast.

7.6 Chemical pre-treatment

There are several different chemical methods by which adherends can be cleaned and prepared for bonding including: solvent cleaning, detergent wash, acid etch, anodising and primers. However, in the case of composite materials, the list is somewhat reduced in that most composite resins have a high surface free energy and little or no change in surface chemistry with regards to the bulk.

Solvent cleaning in its simplest form can be performed by using a suitable cloth to apply the solvent to the adherend. The cloth should be applied so that the surface is wiped in one direction only, to prevent any surface debris from being re-deposited. The cloth should also be replaced regularly.

Consideration must be given to local or national environmental regulations on the use of organic solvents especially with respect to volatile systems. Many 'tried and tested' systems are being phased out and it is important that the end user is familiar with the replacements e.g. application method, drying times etc.

7.7 Energetic pre-treatment

Energetic surface pre-treatments which have been reported in the literature include corona discharge, plasma, and flame and excimer laser. All of these procedures cause a change in the surface texture of the adherend, brought about by the interaction of highly energetic species with the adherend surface. These pre-treatment methods have been applied to metals and in particular composites and plastics.

7.7.1 Plasma

Plasma is an excited gas consisting of atoms, molecules, electrons, ions and free radicals. Applying a high frequency and high voltage between, for example, parallel plate electrodes in a low-pressure chamber, generates plasma. The advantage of this method is that it allows treatment of adherends by different plasmas of argon, ammonia, oxygen or nitrogen.

Plasmas created from inert gases are generally used to clean the surfaces of adherends. The excited species generated can have one or more of the following effects on the adherend:

- Surface clean: The excited species may have sufficient energy to displace some surface contaminants.
- Degradation and ablation: The plasma can cause degradation of the surface of polymeric materials and lead to removal of debris from the surface.
- Cross-linking: The surface of the adherend may become cross-linked and prevent the formation of weak boundary layers.

- Oxidation: The plasma can lead to introduction of oxygen-containing groups, for example carbonyl, brought about by oxidation of the polymer surface; this can lead to the adherend being readily wetted by the adhesive.

7.7.2 Lasers

More recently, laser ablation has been employed to prepare composite surfaces for adhesive bonding. In contrast to plasma processes, lasers deliver a focussed beam of energy at the substrate surface which can induce ablation by vaporisation of the matrix resin. Depending upon the nature of the laser and associated optics, the beam can be pulsed or continuous enabling the rapid processing of both large areas and discrete regions. The speed of the process enables material to be removed with little or no damage to the surrounding areas and embedded fibres can be exposed intact.

In a similar manner to plasma cleaning, the laser can impart additional chemical functionality to the composite surface, thereby enhancing adhesive bonding. By varying the power and focus of the beam, the surface topography can be manipulated too. However, in contrast to plasma, lasers can only operate through line of sight, meaning that shadowing can be an issue and internal surfaces cannot be processed. Additionally, laser ablation generates considerable fumes which require careful extraction. The process should therefore be carried out in an isolated cell environment to ensure appropriate health and safety controls.

7.8 Pre-treatment selection

Correct selection of an appropriate pre-treatment is highly dependent upon the adherend composition, structure, properties (mechanical and chemical) and end function. The large majority of the processes described in the previous sections can be applied, at least in part, to most adherends. However, as the process becomes more targeted towards activating the surface chemistry of the adherend, so the process must become more tailored. This is particularly relevant to chemical and energetic processes. Additionally, it is not always necessary to select the ‘best’ pre-treatment process when the functional requirements of the final structure do not demand it; cost and pre-treatment time may have a significant impact on the final process selected.

In the case of composite materials the most significant aspect to consider is the chemistry of the matrix or resin material. For most thermoset systems, the resins employed are either epoxy or polyester in type. Such resins exhibit high surface free energies once cured and can therefore be pre-treated via some type of abrasive or ablation process in tandem with appropriate removal of loose material/contamination through solvent wiping etc. In the case of thermoplastic composites, the situation is more complex as the resins employed comprise a number of very different chemistries, most of which have a low surface free energy. The commonest resins are PEEK, PEK, PPS, PE and PP, all of which present bonding challenges. In view of this, where possible such materials are therefore preferentially welded rather than bonded, but if bonding is required then the only realistic options are to pre-treat using either energetic technologies (plasma and laser) or possibly some type of chemical etch. It should be stressed that such etches are often complex and hazardous and should only be considered as a last resort. It is for this reason that such approaches are not detailed in this Guide.

8. NON-DESTRUCTIVE TESTING (NDT)

The unique composite structure of FRPs inevitably leads to the complex combination of possible defects arising through material production and part production at the same time. Composite materials cannot be checked for quality before the parts are made, or even joined in the case of co-curing. The exception is thermoplastic composites that can be impregnated and consolidated into flat sheets for subsequent thermoforming into finished parts. The manufactured sheets can be inspected for defects before progressing to the next manufacturing stage. Defects that affect the performance of composite joints are determined by those created during the part manufacture and those appearing due to the joining process.

Composites will always contain some defects; it is impractical to manufacture these materials with perfect fibre alignment and distribution, with every fibre completely wetted over its entire surface and with zero voids, contamination or foreign material. The question is 'what kind/size/amount of defect is unacceptable, and must be found?' This is a decision to be made by the designers, and is outside the scope of this Guide.

However, inspection (non-destructive) is an important aspect of the broader subject of joining composites, and this section provides a review of the commercial off-the-shelf (COTS) inspection techniques suitable for the inspection of FRP components. To avoid potential confusion, the terms NDT (non-destructive testing), NDE (non-destructive evaluation/examination) and NDI (non-destructive inspection), although subtly different, will be grouped into the single term NDT in this Guide.

8.1 Typical defects

Defects that can have an impact on the performance of composite joints include:

- Degree of resin cure (thermoset composites)
- Fibre volume fraction
- Fibre wrinkling/waviness (±0.25mm over 50mm)
- Delamination (surface and deep)
- Lack of adhesion (kissing bonds)
- Inclusions, porosity and voids
- Incorrect fibre alignment
- Surface texture

It is rare for a single NDT technique to be able to detect all defects and material property parameters. Most NDT practitioners agree that the best approach is to employ a number of complementary methods. This may, however, not be possible due to budget constraints.

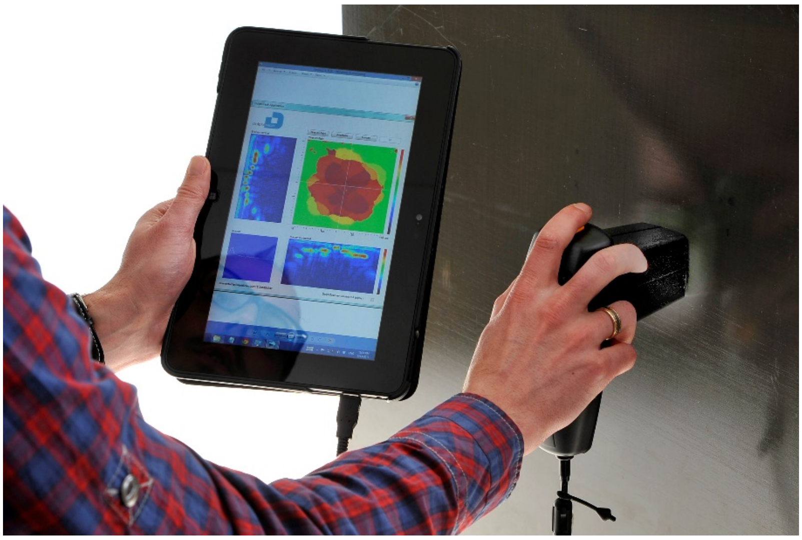

Figure 34: Ultrasonic inspection. Photo: JR Technology

8.2 Inspection techniques

Inspection techniques commonly used to inspect composites and composite joints are listed, with specific variants, below:

- Visual inspection
- Tap testing
- Ultrasonic testing (UT)
    - Conventional A, B and C-scan
    - Phased array
    - Time of flight diffraction (TOFD)
    - Full matrix capture (FMC)

- Laser shearography
- Thermography
- Radiography
    - 2D radiography
    - X-ray computed tomography (CT)
- Acoustic emission
- Vibrational analysis methods
    - Membrane resonance
    - Mechanical impedance analysis

These are briefly discussed in the following sections, along with some techniques specific to bolted joints using electrical resistance change, strain gauges and vibration techniques.

Other NDT methods used for composites which may be less relevant for joining include: Electromagnetic testing, terahertz imaging and spectrosopic methods for cure monitoring.

A more thorough reference on NDT of composites and composite joints can be found in Williams et al (2002).[38]

8.2.1 Visual inspection and tap testing

Visual inspection should be carried out before any other NDT technique is used. It may identify variables that will hinder the NDT inspection and can identify obvious defects accessible to the surface. A trained inspector typically is looking for resin starvation, edge delamination, fibre break-out, and other types of discontinuities present on the exterior of the item inspected. Magnification may be used.

The tap test is the oldest and simplest method of inspecting adhesive bonds. The bonded item is lightly tapped with a tap hammer or a coin to detect disbonds. Judgments are based on comparing the acoustic response from the material under test. A typical well bonded area will produce an even pitch sound compared to a disbonded area which usually produces a dead or dull sound. Tap testing should be limited to near surface inspection of bondline defects. It is not suitable for bond lines at a depth of more than a few mm, or for complex joints or assemblies.[33]

Visual and tap testing are useful but should inform, but not replace, subsequent NDT inspection.

8.2.2 Ultrasonic testing (UT)

Ultrasonic testing of metals and alloys is a common practice within industry. Ultrasonic waves employed have frequencies between 100 kHz and 25 MHz. Higher frequencies provide a better spatial resolution but are also more attenuated. UT for use with composite materials is more difficult due to the higher attenuation of the material, caused by resin/laminate boundaries. Furthermore, the anisotropic nature of composites means that the speed of sound varies with fibre orientation. Together this provides a unique challenge when undertaking ultrasonic testing on composite materials. Several different techniques are available, depending on the type of defect of interest, the resolution required, the depth of the defect, and the materials and budget

Figure 35: Rapid automated ultrasonic inspection of an aerospace component in the IntACom project

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[33] Register, J.D., 1998: 'Nondestructive testing of aircraft composites'. Aviation Pros. https://www.aviationpros.com/home/article/10389135/nondestructive-testing-of-aircraft-composites [Accessed 2/1/20]

available. The process is easily automated for rapid inspection of large structures (Figure 35).[34]

More recent developments in UT inspection have yielded improvements through Phased Array and Full Matrix Capture systems that are particularly useful for inspecting composites.

8.2.3 Laser shearography

Laser Shearography uses monochromatic laser light to illuminate the surface of a component. If the surface is optically rough e.g. not a mirror surface, the light reflected will generate a speckle pattern which is recorded by a digital camera. When the component is stressed, e.g. by a vacuum or heat, the speckle pattern will change as the component deforms. By recording the new speckle pattern, and subtracting it from the original speckle pattern, a shearographic fringe pattern is produced and displayed on a computer screen. When there is a subsurface feature such as a defect (e.g. a void, crack, or delamination), or a stringer, the regular fringe pattern will be disturbed.[35]

Depending on the material strength and depth of defects within a sample, Shearography can detect most discontinuities that occur in composite structures, including disbonds; delaminations; cracked core; crushed core; wrinkling; fluid ingresses; porosity; cracks; repair defects; and impact damage (BVIDs). Additional structural information such as ply drops, bulkheads, overlaps, splices, stringers, ribs can also be detected.[36]

8.2.4 Thermography

Infrared thermographic testing is a NDT method that images thermal patterns on the surface of a component to detect subsurface indications. A sensitive infrared camera observes the radiation emitted from the surface of a specimen to produce thermograms. Active testing using either pulsed or lock-in thermography are the most used techniques for NDT.

Thermography has been used for the inspection of thin GFRP components for many years, especially in the wind-power, marine and aerospace sectors.[37] A general limitation of using thermography is the depth penetration as the heat dissipates within a material. A general rule of thumb is that the radius of the smallest detectable defect should be at least one to two times larger than its depth under the surface.

8.2.5 Radiography

The principle of radiographic inspection methods is to let high frequency electromagnetic radiation (x-rays or neutrons) pass through a component and monitor changes in intensity. The observed changes form an image known as a radiograph. Attenuation of the radiation depends on the density and thickness of the material it passes through, so defects such as voids, under-cured areas, and disbonds can be detected.

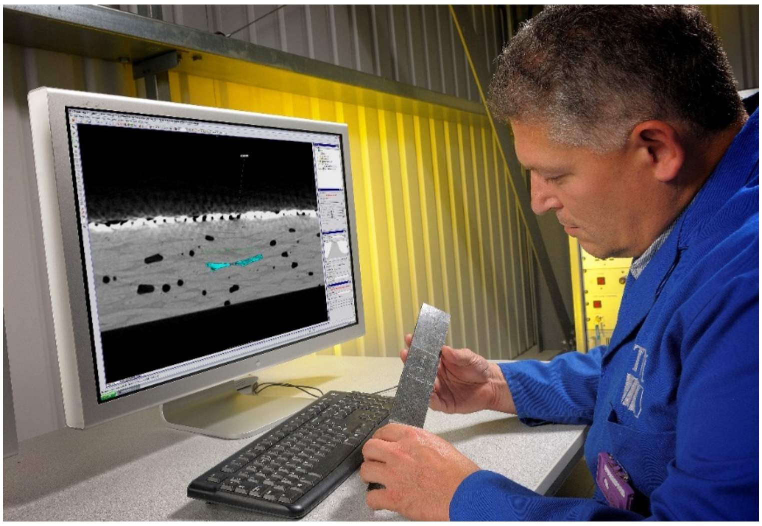

Figure 36: Orthogonal plane view X-ray CT inspection of a composite panel. Copyright © 2020 TWI Ltd reproduced with permission

The two main radiographic testing methods are conventional 2D radiography and computed tomography (CT). 2D radiography (Figure 36) produces a superimposed image through the thickness of the composite, so no depth information is provided. Whereas CT scanning produces 3D

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[34] Cooper I, Nicholson I, Yan D, Wright C and Mineo C, 2013: 'Development of a Fast Inspection System for Aerospace Composite Materials - the IntACom Project'. 9th International Conference on Composite Science and Technology (ICCST-9), Italy, 2013

[35] See https://www.twi-global.com/what-we-do/services-and-support/asset-management/non-destructive-testing/ndt-techniques/laser-shearography [Accessed 2/1/20]

[36] See https://www.dantecdynamics.com/solutions-applications/solutions/laser-shearography-ndt/ [Accessed 2/1/20]

[37] Müller J P and Krankenhagen R, 2019: 'Optimizing thermographic testing of thick GFRP plates by assessing the real energy absorbed within the material', Composite Structures, vol. 215, May, 2019. pp. 60-68, 2019.

volumetric data, depth information is readily available, along with length-width.

Conventional radiography was traditionally performed with photographic films but as detector technology has advanced, digital radiography has become commonplace.

The resolution and effectiveness of radiographic methods can be enhanced by using penetrant dyes which enter the cracks and show up clearly on a radiograph. This does, however, require the cracks to be surface-breaking for a penetrant to enter.

8.2.6 Acoustic emission (AE)

Transient elastic waves are generated by the release of energy from localised micro-structural changes in the material when a composite structure is loaded. In order to detect defects, piezoelectric transducers attached to the surface of the material are used to convert these high frequency acoustic emission (AE) waves into electrical signals.[38]

The AE parameters generally monitored are amplitude, hits, counts, energy and their cumulative values. When the AE data are superimposed on the load–deflection curve or torque–tension curve, a clear picture of the failure mechanism in the joint being tested emerges.

It is possible to study the bearing failure mechanism of CFRP bolted joints using a typical superimposed load response and AE count with time.[39] AE counts increase rapidly at various stages indicating that bearing damage is progressive. Four different stages of the mechanism have been identified:

- Damage onset
- Damage growth
- Local fracture
- Structural failure

One important aspect in using mechanical fastening is how much preload or clamp-up load can be applied via the fastener. In one study, bolt failure occurred due to thread stripping before the composite specimen failed, and an exponential increase of AE hits was observed as the failure of the bolts became imminent.[40] AE energy levels monitored while tightening the composite joints beyond the torque limit recommended by the MSFC-STD-486B standard for metallic joints[41] has shown that no AE responses were detected at the specified torque limits and therefore the torque limit was concluded to be safe for tightening composite joints.[42] Therefore, testing the bolt strength separately and monitoring the AE signals may be important. By comparing the AE signals generated during the bolted composite joint test with the AE signals from the bolt alone, the source of the signals can clearly be distinguished.

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[38] Williams S, Smith F, Court R and Warwick M, 2002: 'Best practice guide on NDT of thermosetting and thermoplastic polymer composites'. TWI document.

[39] Xiao Y and Ishikawa T, 2005: 'Bearing strength and failure behaviour of bolted composite joints (part I: experimental investigation)'. Composites Science and Technology, Volume 65, Issues 7-8, Pages 1022-1031.

[40] Kostreva K M, 2002: 'Torque limit for bolted joints for composites Part B: experimentation'. NASA/MSFC.

[41] NASA, 1993: 'Standard, Threaded Fasteners, Torque Limits For'. Document Number MSFC-STD-486, Revision B, 1993-02-09.

[42] Thomas F P and Zhao Y, 2005: 'Torque limits for composites joined with mechanical fasteners'. In: 46th AIAA/ASME/AHS/ASCE/ASC structures, structural dynamics and materials conference.

8.2.7 Vibrational analysis methods

Vibrational analysis methods are particularly useful for assessing core disbond. There are three methods which all rely on the stiffness of the material under test. These are resonance, mechanical impedance analysis (MIA) and pitch-catch. Each different method has their strengths and weaknesses so in practice a combination of these is often used.[43]

8.2.7.1 Membrane resonance

See where the probe is over a good area it is dampened and the amplitude and phase are as position A. Where there is a disbond present, the skin is less stiff and so the amplitude and phase of the probe signal is changed, as per position B. See Figure 37.

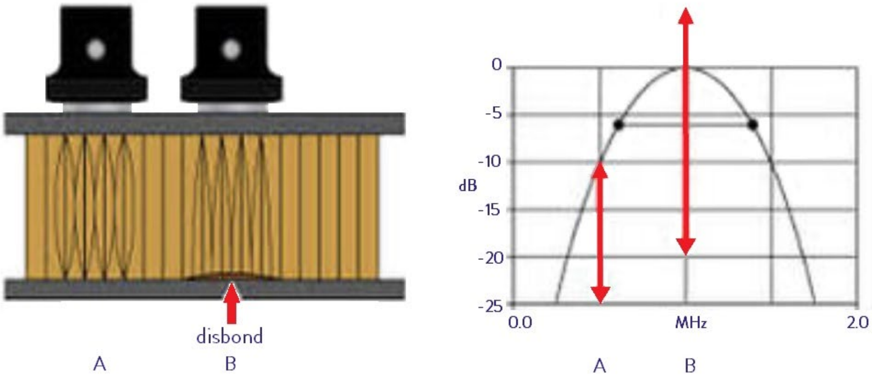

Figure 37: Membrane resonance. Image: MTD Group (adapted)

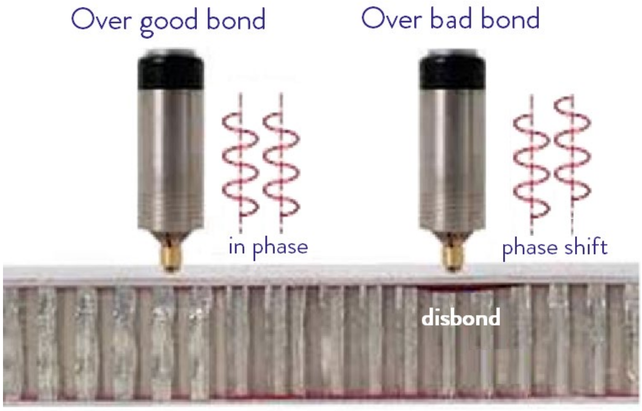

Figure 38: Mechanical impedance analysis. Image: MTD Group (adapted)

8.2.7.2 Mechanical impedance analysis (MIA)

This technique uses a single point of contact and is particularly useful in the detection and sizing of the bond/disbond location. Mechanical Impedance Analysis (MIA) has for many years provided sound technology to aerospace and composite bond testing. Being able to analyse response signals from materials in both amplitude and phase at either single or dual frequencies is many times more sensitive than 'tap testing' and more rapid. See Figure 38.

8.2.7.3 Pitch-catch

A dual tip probe is placed onto the surface of a component and a short tone burst or pulse is sent into the material from one probe tip and received by the other. See Figure 39.

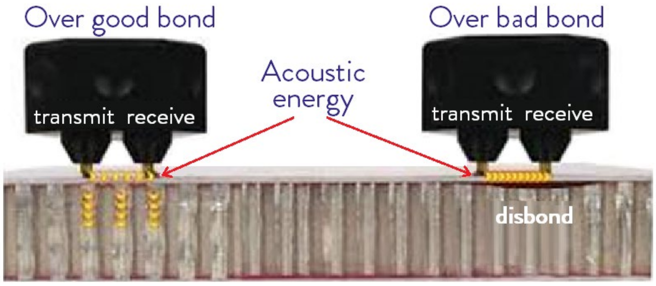

Figure 39: Pitch-catch. Image: MTD Group (adapted)

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[43] Text and figures in this section adapted with permission from Minton, Treharne and Davies Ltd, Composite Inspection division. See https://minton.global/

8.2.8 Other techniques for bolted joints

8.2.8.1 Electrical resistance change technique

Since carbon fibres have higher electrical conductivity than most other fibres used to produce composite materials, a number of studies have been carried out on electrical measurements for CFRP laminates. Compared with isotropic materials, where current flows along the shortest path between two electrodes, in composite materials the electric current flows more readily in the fibre direction.[44] (This is not relevant to composites with glass or other non-conductive fibres.)

Current measurements have successfully been used in detecting stresses and strains as part of health monitoring systems.[45] These methods can be used to classify different failure mechanisms in CFRP subjected to both static and dynamic loading conditions. If there is any fibre breakage caused by bearing failure, the current flow path can change due to alterations of the electrical resistance of the joint.

The potential to detect damage arising in composite bolted joints, and the use of the electrical resistance method as a successful technique for identifying bearing failure has been demonstrated. Bearing failure of bolted composite joints consists of compressive failure, matrix cracks, delamination, kink band formation, and other phenomena. Detecting bearing failure is important for assuring integrity of composite structures. Conventional non-destructive inspection methods, such as C-scan and X-ray inspection, are commonly used to detect bearing failure, however these conventional inspection methods are expensive, sometimes cumbersome, and time-consuming. Fibre breaking and delamination induce a permanent increase in the electrical resistance of bolted composite joints, and this method offers potential for low-cost inspection and for detection of bearing failure.[44] [46]

8.2.8.2 Bolt gauge

The use of strain measurements in the fastener to monitor the bearing damage in composite and metallic joints has been demonstrated.[47] [48] This method offers a simple and low cost self-diagnostic technique. The strain developed in the fastener is measured by a strain gauge installed on the surface of the fastener head. The principle is that bearing damage produces out-of-plane compressive deformation in composite laminate, and this deformation affects the bolt tension which can be detected by a strain gauge bonded to the bolt head.

8.2.8.3 Vibration techniques

Vibration techniques are used to investigate the effects of bolt preload/torque in composite bolted joints. They are based on structural dynamics principles and is applied by subjecting the structure to vibratory loads. As a global method for damage detection in composite materials, it has been used to detect delamination in flat plates, beams and curved panels.[49] [50] [51]

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[44] Shimamura Y, Oda K, Todoroki A and Ueda M, 2006: 'Detectability of bearing failure of composite bolted joints by electric resistance change method'. Key Engineering Materials, Volumes 321-323, Pages 957-962.

[45] Kupke M, Schulte K and Schuler R, 2001: 'Non-destructive testing of FRP by d.c. and a.c. electrical methods'. Composites Science and Technology, Volume 61, Issue 6, Pages 837-847.

[46] Shimamura Y, Oda K, Todoroki A, Kobayashi H and Inada T, 2005: 'Application of electrical resistance change method to damage detection of CFRP bolted joints'. Key Engineering Materials, Volumes 297 - 300, Pages 653-658.

[47] Xiao Y, Kakuta Y and Ishikawa T, 2004: 'A self-diagnostic technique for the bearing damage of composite joints'. Proc US–Japan Conf Comp Mat: 9–11.Yonezwa, Japan.

[48] Xiao Y, Kakuta Y and Ishikawa T, 2007: 'A new concept for structural health monitoring of bolted composite joints'. Key Engineering Materials, Volume 334-335, Pages 465–468.

[49] Schulz M J, 1997: 'Health monitoring of composite material structures using a vibrometry technique'. NASA - CR - 205070.

[50] Mickens T, Schulz M J, Sundaresan M, Ghosal A, Naser A S and Reichmeider R, 2003: 'Structural heath monitoring of an aircraft joint'. Mechanical Systems and Signal Processing Volume 17, Issue 2, Pages 285-303

[51] Doebling S W, Farrar C R, Prime M B and Shevitz D W, 1996: 'Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review'. Los Alamos National laboratory 1996; Report LA - 13070 - MS.

8.3 NDT Comparison

Table 7 shows a comparison of the applicability of the most relevant NDT methods, and can be used as an initial guide for the selection of an appropriate NDT process to detect particular defects that relate to joint performance.

Table 7: Summary of the various NDT techniques and their applications. (10 = best)

	Visual	Tap test	UT (A-Scan)	UT (PE B-Scan)	UT (C-Scan)	Ultrasonic depth scan	Laser shearography	Thermography	Radiography	Acoustic emission	Vibrational analysis
Delamination (small)	0	2	5	8	9	9	9	8	7	8	4
Delamination (large)	0	4	8	10	10	10	10	10	7	8	6
Cracks	5	0	0	0	0	0	9	4	8	9	0
Disbonds	0	4	8	10	10	10	10	10	7	8	6
Voids	0	1	6	6	10	6	5	5	10	6	1
Impact	5	4	10	10	10	10	10	8	4	10	6
Porosity	0	0	5	6	9	4	8	6	10	4	0
Inclusion	0	2	7	7	9	6	7	7	6	3	4
Erosion	3	0	9	10	7	10	5	7	4	3	0
Core splice	3	5	1	2	6	0	8	4	8	3	5
Core disbond	0	10	8	9	10	8	10	10	5	6	10
Core crushing	2	10	5	5	8	0	5	5	5	5	10
Matrix cracking	3	0	0	0	0	0	0	0	6	7	0
Fibre breakage	1	4	0	0	0	0	6	0	5	10	4
Kissing bond (adhesion)	0	1	0	0	1	0	5	2	0	0	1
Water ingress	3	0	4	5	8	0	4	10	5	1	0
Fibre waviness	2	0	1	8	9	0	4	2	2	0	0
Fibre alignment	2	0	0	1	9	0	2	2	5	0	0
Incomplete cure	0	0	0	5	2	5	0	0	0	0	0
Excess resin	1	0	0	5	5	8	5	6	2	0	0
Excess fibre	1	0	0	5	5	8	5	6	2	0	0

9. TESTING AND STANDARDS

Testing requires specific skilled personnel and test equipment, and can be carried out by a number of organisations within the UK which typically have accreditation from the United Kingdom Accreditation Service (UKAS).

Figure 40: Single lap shear testing of an adhesively bonded joint. Copyright © 2020 TWI Ltd reproduced with permission

More detailed information on testing can be found in the NPL Manual, 'Design and Testing of Bonded and Bolted Joints'.[52]

Appendix 2: Standards contains a list of standard test methods pertinent to polymeric composite materials, developed by the international standards bodies such as BSI, ISO, ASTM and CEN. The aim of these standards is to provide test methods to assist engineers in designing efficient and reliable mechanical joints in composite structures.

The presence of a mechanical fastener in a structure necessitates there being a hole to accommodate the fastener. Therefore, mechanical tests to determine the tensile and compressive strength of composite laminates containing open or filled holes are important and are specified in the relevant international standards. In addition, test methods that can be performed in order to determine static bolt bearing strength, bolt bearing fatigue response, bearing/bypass interaction response, and pull through characteristics are included.

Adhesively bonded joints are covered sufficiently as the joining technology is well established. Carry-over from bonded metal testing is being replaced by new test methods designed specifically to cater for the laminated and anisotropic nature of composites.

There is currently a severe lack of standards for welded thermoplastic joints; test methods designed for adhesively bonded joints are frequently used in their place.

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[52] NPL, 2007: 'Design and Testing of Bonded and Bolted Joints' [online]. Available from http://resource.npl.co.uk/docs/science_technology/materials/materials_areas/adhesives/publications/manuals/bonded_bolted.pdf [Accessed 24/10/19]

10. DISASSEMBLY

10.1 Introduction

Almost as necessary as the need for joining parts together at the beginning of life of a component or structure is the desire at some point to separate parts in order to carry out maintenance and repair operations or to facilitate recycling at the end of life. Many joints are designed as multiple non-permanent joints; those that must be repeatedly made and then unmade to fulfil their design role. Buttons, bottle tops, zips, press studs, push fit panel clips are well known examples. However, more structural joints such as those connecting the bodies of automobiles, aircraft and buildings are designed to be permanent, or at least long term. The need to facilitate inspection and repair will in many examples necessitate joints being undone to gain access or to replace damaged areas, and the growing requirement for recycling, especially in the automotive industry, inevitably demands ways of separating parts at the end of life. Ideally this is done in a way that maximises the subsequent value of the materials to be exploited through the production of new raw materials. This can present a significant challenge to the designer who must now find a solution that is both permanent and non-permanent.

Figure 41: End of life aircraft scrap. Photo Composites UK

10.2 Disassembling Mechanically Fastened Joints

The majority of mechanically fastened joints are, by their very nature, non-permanent and can be disassembled at some point relatively easily. The integrity of the joint is provided by the presence of an additional part; the mechanical fastener. Removal of this element effects separation of the joint. Threaded fasteners, such as nuts and bolts, can be readily removed provided a suitable tool is available. Other, more permanent fasteners, such as rivets, can be removed by machining out the fastener (drilling), although this approach requires a new fastener to reassemble the joint in the case of a repair or maintenance operation.

Complications arise in the separation of mechanically fastened joints when an additional joining mechanism has been applied. Thread locking compounds are designed to prevent threaded joints coming apart unintentionally in service, and therefore hinder intentional separation. In addition, the use of hybrid joining techniques such as weld/bonding or rivet/bonding introduce the complications of separating the adhesive element of the hybrid joint.

It is important to consider maintenance and repair operations likely to be required in the life of a joined composite structure as this will have significant impact on the choice of mechanical fastening. Components likely to experience frequent removal for inspection are in general attached using quick release 'Camloc'/'AeroLoc' type fasteners that provide sufficient integrity and are easily separated when required, often by hand, without the need for a special tool.

10.3 Disassembling Adhesively Bonded Joints

One of the advantages of adhesive bonding as a joining technique is the ability to form connections that are very difficult to either accidentally or intentionally separate afterwards. However, the ability to debond (disassemble) an adhesively bonded joint at some point is useful when both repairing and recycling a structure.[53] The common approach is to use mechanical force to break the joint or use heat if the joint is made using a hot melt adhesive. Mechanical force works well if the parts are small, but does not provide an efficient solution when large structures need to be disassembled, in which case large equipment is needed to carry out the process. Solvents or acid immersion may also be used, but there are health and safety concerns which arise. Combustion may be an option, although the environmental effects of burning large volumes of organic adhesive need careful consideration. Combustion also does not yield parent adherend materials that could be reused or recycled on their own. Adhesive bonding has been shown to offer many benefits as a joining technique. However, despite these attractive advantages, adhesive bonding is not the solution to every joining problem and the technology suffers through difficulty in disassembling joints making maintenance, repair or recycling difficult.

Products and techniques have been developed to create debond/disbond-on-demand systems that make disassembly of bonded parts easier, safer and more cost effective. These include: [54]

- Thermally expandable particles (TEPs)
- Electrically activated
- Nanoparticles
- Diels-Alder chemistry

10.3.1 Thermally expandable particles

Banea et al (2015)[55] suggested adding TEPs into an epoxy adhesive to facilitate debonding for disassembly. In their research, 'Expancel 031 DU 40' from Expancel Nobel (Sweden) was selected as a TEP to add to an epoxy and polyurethane adhesive. TEP sizes range from 10 to 16μm and expand approximately 200% on application of sufficient heat.

Induction heating of steel substrates was used to demonstrate the debond-on-demand performance of single lap shear coupons. Other work has reported similar success with the approach, and quoted easy disassembly at a temperature of 250°C.[56] The relative ease of separation of the particles does depend on several factors including:

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[53] Broughton J G, Hutchinson A R, Winfield P, 2018: 'Dismantlable adhesive joints for decommissioning, repair and upgrade'. NATO STO-MP-AVT-266-21 Specialist Meeting: Use of bonded joints in military applications, 16-18 April 2018, 2018, Turin, Italy.

[54] Banea M D, da Silva L F M and Campilho D S G, 2013: 'An overview of the technologies for adhesive debonding on command'. Annals of "Dunarea de Jos" University of Galati, Fascicle XII, Welding Equipment and Technology, Volume 24, 2013, Pages 11-14

[55] Banea M D, da Silva L F M and Carbas R J C, 2015: 'Debonding on command of adhesive joints for the automotive industry'. International Journal of Adhesion & Adhesives 59 (2015) 14–20.

[56] Kishi H, Imade J, Inada Y, Sato C, Matsuda S and Murakami A, 2007: 'Dismantlable epoxy adhesives for recycling of structural materials'. 16th International Conference on Composite Materials (iccm16), Kyoto, Japan, 2007.

- Thickness of adherends
- Adherend material
- Adhesive type
- Concentration of TEPs
- Time required to separate
- Uniformity of heating
- Maximum temperature resistance of adherends

Debonding generally occurred within 60 to 80 seconds of heating for the epoxy and polyurethane adhesives respectively. Although an attractive debond-on-demand system this is not ideally suited for uptake in composite vessels where there are fire resistance requirements, as during a fire the adhesive would debond, causing collapse of the structure even before it had suffered significant damage.

10.3.2 Electrically activated

In a study by DC Polymers, cross-linking salt (1-Ethyl-3-methylimidazoliumehtylsulfate (EMIM-ES)) was added to the adhesive so that, when stimulated with an electric current, it caused cross-link scission of the polymer, thus degrading the adhesive and enabling separation of the joint.[57]

IEC Laboratories in the USA developed a similar approach that uses electricity to destroy the bonds and release a joint.[58] The technique appears to have all the advantages of not being thermally activated and therefore not accidentally separating the joint in the case of a fire. However, the technology currently only works for joining conductive metals as an electrically conductive path must be created to allow current to flow across the bondline. The adhesive, ElectRelease™ E4, is a two-part, epoxy-based debondable adhesive. ElectRelease™ E4 bonds to most metals including aluminium and its alloys, steel, stainless steel, and copper.

The Company has released a solution to this problem in their ElectRelease™ Foil Patch (EFP) to allow the system to work with non-conducting substrates such as glass fibre composites (Figure 42). However, a metal foil layer is still required and this must be attached to the surfaces of the composite parts being joined.

(a) ElectrRelease™ Foil Patch (EFP)

(b) EFP bonded to nonconductive substrate (e.g. glass fibre composite)

(c) Separated substrates, after current flow

Figure 42: IEC Labs ElectRelease™ Foil Patch system

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[57] Leijonmarck S, Cornell A, Danielsson C-O and Lindbergh G, 2011: 'Electrochemical Characterization of Electrically Induced Adhesive Debonding'. J Electrochem Soc 158, pp109-114.

[58] Haydon D, 2002: 'ElectRelease – electrically disbonding epoxy adhesive'. Assembly Automation, Vol. 22 Issue: 4, pp.326-329.

There is currently no product on the market that performs the same role when separating purely non-metallic composite parts.

10.3.3 Nano-particles

The Evonik Company offers a product called VP AdNano® MagSilica. MagSilica is an adhesive tape containing an iron oxide powder embedded in silicon dioxide nanoparticles.[59] The nanoparticles behave as nanomagnets when subjected to external magnetic field, causing heat to be generated that facilitates curing or debonding. Evonik has been granted a patent for the invention, which has many potential applications.[60] This electro-magnetic induction approach can potentially be used in conjunction with any thermally activated disbonding technique.

The US Army Research Laboratory has also tried a similar approach, and investigated a reactive nanocomposite (RNC) solution for rapid disassembly.[61] The disassembly is thermally triggered and a physical change occurs at the RNC inserted into the bondline. The reactive nanofoil development was investigated and used to demonstrate the feasibility of rapid separation of bonded military structures.

10.3.4 Diels-Alder Chemistry

In the USA, Sandia National Laboratories has developed a thermally removable low modulus adhesive that requires the incorporation into the adhesive formulation of thermally reversible furan-maleimide Diels-Alder adducts.[62] Although successful as a disbond on demand approach, experimental data demonstrated relatively low lap shear strengths (3.36 to 4.65MPa), which make the epoxy formulation somewhat limited as a structural adhesive.

10.4 Disassembling Welded Joints

Welding of polymeric materials (fusion bonding) has many of the same advantages as adhesive bonding, and consequently also suffers from difficulty in disassembling the joint. Thermoplastic composite welding is a thermally activated, reversible process which, in theory, can be repeated at any time to dismantle the joint. However, the practicality of reversal is dependent on the welding process initially selected. Welding processes that required the surface of both joining parts to be exposed prior to joining (laser, hot bar, hot plate, hot gas, Infra-red etc) are difficult to reverse as the surfaces cannot easily be reheated. Likewise, linear friction (vibration) welded joints cannot be dismantled by simply repeating the welding process. Techniques such as induction, microwave, resistive implant and laser transmission welding can be reversed by simply re-applying the same heating mechanism. This does require the original edges of the resistive implant to be accessible in the case of resistive implant welding, although this can be accommodated through design for disassembly.

An advantage that welded joints have over thermally activated disbonded adhesive joints is that the welds can subsequently be remade, the thermoplastic is able to be reheated a number of times, whereas after thermal degradation of the adhesive it must be cleaned off and replaced by fresh adhesive. In each case, however, careful consideration should be taken to ensure subsequent joining, whether it is re-welding or re-bonding, is carried out correctly.

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[59] Evonik, 2009: 'NanoCare Project Builds Trust' [online]. Available from https://corporate.evonik.com/en/Pages/article.aspx?articleId=106624. [Accessed 12 July 2019].

[60] Kolbe J, Kowalik T, Popp M, Sebald M, Schorsch O, Heberer S, Pridohl M, Zimmermann G, Hartwig A and Born E, 2004: 'Curable bonded assemblies capable of being dissociated'. US 20040249037, (Patent).

[61] Minnicino M and Sands J M, 2011: 'Reactive nanocomposites for controllable adhesive debonding'. US Army Research Laboratory report ARL-TR-5649

[62] Aubert J H, 2003: 'Thermally removable epoxy adhesives incorporating thermally reversible Diels-Alder adducts'. J Adhes, 79(6), 2003, 609-616.

10.5 Comparison of techniques

Lu, Broughton, et al[63] reviews disbonding techniques for automotive dismantling, and includes a useful table comparing and rating techniques which has been adapted in
Table 8.

Table 8: Comparison and Rating of Disbonding Techniques. Adapted from Lu, Broughton, et al [63]
Overall Rating: 1 to 5* from low to high.

Techniques	Disbonding condition	Applicability to composites	Complexity	Capital Cost	Disbonding efficiency	Overall rating*
Mechanical separation	N/A	Low	Low	Low	Low	*
Mechanical fasteners (non-permanent)	N/A	High	Low	Low	High	****
Mechanical interlocking tapes (e.g. Velcro)	N/A	Medium	Low	Low	High	***
Electrically activated	Electric Current	Low (unless foil patch)	High	High	High	** (***)
Thermally expandable particles	Temperature (120 -500°C)	High	Medium	Medium	High	****
Thermally reversible chemical structure	Temperature (100 -250°C)	Medium	High	Medium	Medium	**
Thermally removable adhesive (melt)	Temperature (90 °C)	Low	High	Medium	Medium	**
Oxidising agents	Temperature (300 °C)	Low	Medium	Medium	Medium	*
Microcapsules (encapsulated solvents)	Temperature (175 °C)	Medium	High	Medium	Medium	**
Chemical foaming agents (CFAs)	Temperature (130 -250°C)	Medium	Medium	Medium	High	***
Light sensitive switchable adhesive	Exposure to light (20 seconds)	Low	High	High	High	**

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[63] Lu Y, Broughton J G and Winfield P, 2014: 'A Review of Innovations in Disbonding Techniques for Repair and Recycling of Automotive Vehicles'. International Journal of Adhesion and Adhesives, Volume 50, April 2014, pp119-127

11. NEXT STEPS AND FUTURE DEVELOPMENTS

11.1 Introduction

This report has given an overview of composite joining technology as it stands. Many of the solutions are mature techniques and processes that have been in use since composite materials first attracted the attention of designers and structural engineers. However, this does not mean that there is nothing left to do. Although there are many joining techniques available for the composites industry, no single solution is the outright best and each will have its own relative advantages and disadvantages.[64] Sometimes it can seem almost impossible to find the right joint, and as a consequence the selection of composite materials may not have been the best for that particular application. This means that we are sometimes not able to fully exploit the benefits of composites due to a lack of understanding or choice in the joining technology. Some of the areas most deserving of future research are:

- Hybrid joints
- Joint design at early design phase
- Kissing bond detection
- Recycling/ design for disassembly
- Welding process quality assurance
- Standards & test methods
- Material database

11.2 Hybrid joints

As structures become ever more optimised there is a growing need to include the right material in the right place, and therefore hybrid (multi-material) joining is becoming a growing area of research. In a recent review[65] the increase in research publication of the subject of hybrid joining showed a dramatic increase in the past 15 years (Figure 43).

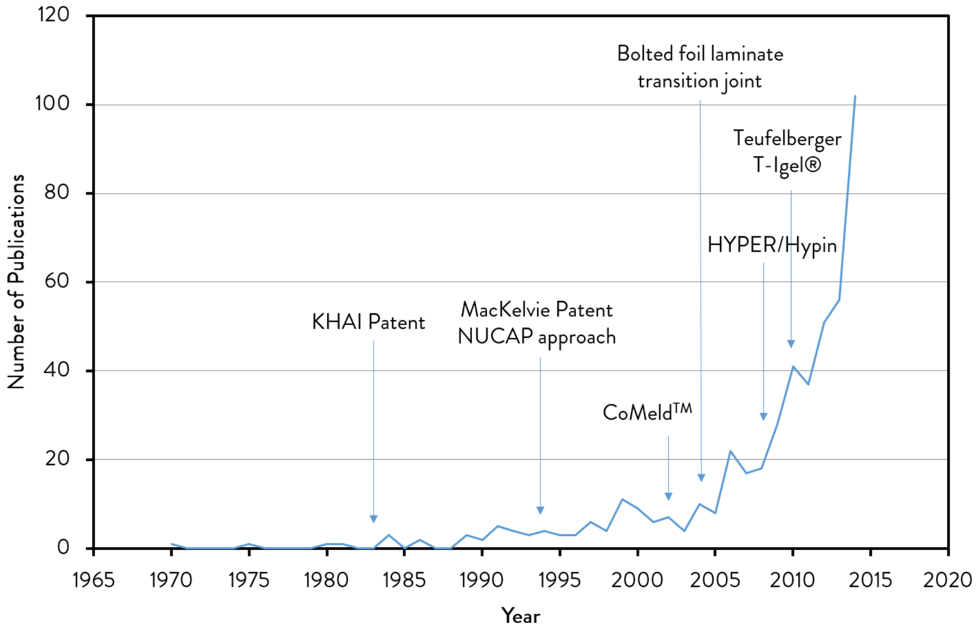

Figure 43: Depiction of number of research publications with publication year covering the area of composite/metal joining with points at which some key approaches/innovations have been reported. [65]

Despite the proliferation of activity very few of these research projects have resulted in commercial systems being developed. The automotive and aerospace markets are keenly awaiting reliable hybrid joining solutions.

11.3 Joint design at early design phase

It has often been the practice to design and manufacture parts and then consider how to join them. Established mechanical fastening or adhesive bonding approaches, successfully applied to metallic structures in the past, have been assumed to translate to use with composite materials, and as a result failures have occurred. Not only is this approach expensive, and possibly a danger to life, it also results in a poor reputation for composites as they are often considered to be the cause of

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[64] Todd S M, 1990: 'Joining thermoplastic composites'. Proceedings of the 22nd International SAMPE Technical Conference, vol. 22, 1990, pp 383-392

[65] Kellar E J C and Worrall C, 2018: 'A review of composite to metal joining using through-thickness enhancement (hybrid joining)'. NATO STO-MP-AVT-266-21 Specialist Meeting: Use of Bonded Joints in Military Applications, 16-18 April 2018, 2018, Turin, Italy

failure. It is critical for the continued growth in composite materials and their structural applications that joint design is considered at an early stage.

11.4 Kissing bond detection

Despite the large number of established non-destructive testing techniques available there is still no widely accepted reliable way to detect the adhesive kissing bond. The aerospace industry insists that for any bonded joint, the failure of which would result in catastrophic loss of the aeroplane, the limit load capacity must be substantiated by one of the following methods: proof testing on each production article, prevention by design features (additional mechanical fastener) or repeatable and reliable non-destructive inspection techniques.[66] [67] As no reliable technique currently exists, and proof testing is impractical, the remaining solution is the inclusion of additional mechanical fasteners, at the additional expense of financial cost, weight and the associated issues with drilling holes in composites.

11.5 Recycling/ design for disassembly

Consideration needs to be given to disassembly of joints to facilitate effective recycling. This 'design for disassembly approach' will continue to attract increasing attention as the global awareness of the importance of recycling man-made materials intensifies and legislation becomes more stringent.[53] [68]

11.6 Welding process quality assurance

There is a multitude of thermoplastic composite (TPC) welding processes available, each with its own advantages and disadvantages.[69] However, despite the apparent countless solutions there is still a lack of widespread uptake of welding as a joining solution for composites. Since the introduction of thermoplastic composite materials such as APC-2 (AS4 carbon fibre reinforced polyetheretherketone (PEEK)) in the 1980s, many studies have been carried out on fusion bonding of TPCs. Of the numerous techniques available, three in particular have been the subject of many research studies as they are considered most suitable for industrial applications; induction, resistive implant and ultrasonic.[70] This is, in part, due to a lack of control of the welding process. Welding often takes place at unseen interface, with heat generation dependent not only on applied parameters such as power or proximity, but also material properties such as electrical and thermal conductivity. As these can be highly anisotropic in composites, and can depend on temperature, methods for assuring repeatable and reliable welded joints still need to be developed.

11.7 Standards, test methods and materials databases

Composite materials are still relatively young compared to metals that empowered the industrial revolution in the 19th century and ceramics that have been used in structures standing for thousands of years. There are, consequently fewer test methods, standards and materials databases for these blossoming materials. This can make material selection itself more uncertain when designing with composites, and also lead to further scepticism in the performance of composite joints. It can, of course, be extremely expensive to comprehensively characterise each and every composite material, including joining, and therefore there is a reluctance to share data. Continued research into the behaviour of joints will result in the establishment of new test methods to characterise, for example, welded joints, and therefore increase the reputation of composites not only as attractive materials but also as being reliable when assembled using joints.

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[66] EASA, 2007: 'Certification Specifications for Large Aeroplanes'. CS-25, Book 1, Airworthiness Code, Amendment 3, 19 September 2007

[67] EASA, 2015: 'Certification specifications and acceptable means of compliance for normal, utility, aerobatic, and commuter category aeroplanes'. CS-23, Book 1, Airworthiness code, Amendment 4, 15 July 2015

[68] Soo V K, Peeters J, Compston P, Doolan M and Duflou J R, 2017:'Comparative Study of End-of-Life Vehicle Recycling in Australia and Belgium'. Procedia CIRP 61 (2017) pp 269 – 274

[69] Ageorges C, Ye L and Hou M, 2001: 'Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review'. Composites: Part A 32 (2001), pp839-857

[70] Ageorges C and Ye L, 2002: 'Fusion bonding of polymer composites; From basic mechanisms to process optimisation'. Springer, 2002

11.8 Concluding remarks

Composite materials have an increasing part to play in all areas of technology but regardless of application, it is not possible to realise their full potential until suitable joining approaches are developed and matured, that offer high performance and are cost effective. The solutions are most probably amongst those described but need more focussed research and development for the full potential benefits of composite materials to be realized. In addition, cognisance of the properties of composites at the material selection stage must be complemented by an appreciation of the myriad of appropriate joining approaches available, and how these may be reversed to facilitate disassembly at some point to endorse the compatibility of composites in a world where resource efficiency is an increasing concern.

APPENDIX 1: GLOSSARY & TERMINOLOGY

11.9 Acronyms / abbreviations

Abbreviation	Definition
ASTM	American Society for testing and materials, now ‘ASTM International’ (standards body)
AWJ	Abrasive water-jet machining
BLT	Bond-line thickness
BMI	Bismaleimide
BS	British standard, issued by BSI Group (standards body)
BSI	British standards institution
CEN	Comité Européen de Normalisation; European committee for standardisation (standards body)
CFRP	Carbon fibre reinforced polymer/plastic
COTS	Commercial off-the-shelf
CRES	Corrosion resistant steel
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
EDM	Electrical discharge machining
EN	European norme; issued by CEN
FDA	Food and Drug Administration (US Federal agency)
FRP	Fibre reinforced polymer/plastic
GFRP (or GRP)	Glass fibre reinforced polymer/plastic
HSS	High speed steel
IPF	Institut für Polymerforschung; Leibniz Institute of Polymer Research
ISO	The international organization for standardization (standards body)
LBW	Laser beam welding
Monel	Nickel-copper alloy with high tensile strength and resistance to corrosion
NDE	Non-destructive evaluation
NDI	Non-destructive inspection

Abbreviation	Definition
NDT	Non-destructive testing
NPL	National Physical Laboratory
OHC	Open-hole compression (test method)
OHT	Open-hole tension (test method)
PCD	Polycrystalline diamond
PEEK	Polyetheretherketone
PH	Precipitation hardening
PI	Polyimide
PTFE	Polytetrafluoroethylene
PU	Polyurethane
PVA	Polyvinlyl acetate
RT	Room temperature
TTT	Through-the-thickness
USM	Ultrasonic machining
WC-Co	Cemented tungsten carbides; tungsten carbide (WC) grains in a ductile binder phase, most commonly Cobalt (Co)

11.10 Terminology

Term	Definition
Accelerated ageing test	Short-term test designed to simulate the effects of longer-term service conditions.
Adherend	Body that is or intended to be held to another body by an adhesive.
Adherend failure	Failure of a joint in the body of the adherend.
Adhesion	State in which two surfaces are held together by interfacial bonds.
Adhesive	Non-metallic substance capable of joining materials by surface bonding (adhesion), the bonding possessing adequate internal strength (cohesion).
Adhesive failure	Failure of an adhesive bond, such that separation appears to be at the adhesive/adherend interface.

Term	Definition
Bearing stress	The surface pressure acting on a joint face directly as a result of the force applied by a fastener.
Bond	The union of materials by adhesives.
Bond-line	The layer of adhesive, which attaches two adherends.
Bond strength	The unit of load applied to tension, compression, flexure, peel, impact, cleavage, or shear, required to break an adhesive assembly with failure occurring in or near the plane of the bond.
Butt joint	Joint in which the plane of the bond is at right angles to a major axis of the adherends.
Bulk adhesive	The adhesive unaltered by the adherend.
Clamping force	The compressive force which a fastener exerts on the joint.
Clearance	Difference between the diameters of the fastener and the hole.
Cleavage	Mode of application of a force to a joint between rigid adherends, which is not uniform over the whole area, but results in a stress concentrated at one edge.
Cohesion	The ability of the adhesive to resist splitting or rupture.
Cohesive failure	Failure within the body of the adhesive (i.e. not at the interface).
Countersunk head	A head, the underside of which fits a flared hole. The bearing surface of other types of heads is generally perpendicular to the body axis.
Creep	The time-dependent increase in strain resulting from a sustained load.
Cure	To set or harden by means of a chemical reaction.
Cure time	Time required to affect a cure at a given temperature.
Double lap joint	Joint made by placing one or two adherends partly over one or two other adherends and bonding together the overlapped portions.
Durability	The endurance of joint strength relative to the required service conditions.
Embedment	Localised plastic deformation which occurs in the vicinity of clamped fasteners or in the fastener threads. Embedding is local plastic deformations that occur under the nut face, in the joint faces and in the threads as a result of plastic flattening of the surface roughness.
Environmental test	Test to assess the performance of an assembly under service conditions.
Exothermic	A chemical reaction that emits heat.

Term	Definition
Fatigue life	Number of cycles necessary to bring an adhesive bond to the point of failure when the bond is subjected to repeated cyclic stressing under specified conditions.
Fatigue strength	Force that a joint will withstand when the force is applied repeatedly for an infinite number of cycles.
Fillet	Portion of an adhesive that bridges the adherends outside the bond-line.
Fit	The general term used to signify the range of tightness which may result from the application of a specific combination of allowances and tolerances in the design of mating parts.
Gel	A semi-solid system consisting of a network of solid aggregates in which liquid is held.
Gelation	Formation of a gel.
Glass transition	A reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one.
Hygroscopic	Material capable of absorbing and retaining environmental moisture.
Lap joint	Joint made by placing one adherend partly over another and bonding together the overlapped portions.
Nut	A metal block (solid nut) or sleeve with an internal thread made to assemble with the external thread on a bolt, screw, or other threaded part.
Open time	Time interval from when an adhesive is applied to when the material becomes unworkable.
Peel	Mode of application of a force to a joint in which one or both of the adherends is flexible and which the stress is concentrated at a boundary.
Peel ply	A layer of resin free material used to protect a laminate for later secondary bonding.
Plasticisation	Increase in softness, flexibility, and extensibility of an adhesive.
Post-cure	Further treatment by time and/or temperature of an adhesive to obtain the required properties by curing.
Porosity	A condition of trapped pockets of air, gas or vacuum within a solid material.
Primer	A coating applied to a surface, prior to the application of an adhesive, to improve the performance of the bond.
Preload	The tension created in a fastener when first tightened. Reduces after a period of time due to embedding and other factors.

Term	Definition
Relaxation	The loss of clamping force in a bolt that occurs typically without any nut rotation occurring. Commonly occurs as a result of embedment but can also be due to gasket creep, metal creep (at elevated temperatures), differential thermal expansion and stress relaxation.
Rivet	A headed fastener of some malleable material used to join parts of structures inserting the shank through a hole in each piece and forming a head on the headless end.
Scarf joint	Joint made by cutting identical angular segments at an angle less than 45° to the major axis of two adherends and bonding the adherends with the cut areas fitted together to be co-planar.
Service life (N)	Number of stress cycles applied to a specimen until it has reached the chosen end of the test.
Shank	Portion of a bolt which lies under the head.
Shear	Mode of application of a force to a joint that acts in the plane of the bond.
Shelf life	The period for which the components of the adhesive may be stored, under the conditions specified by the manufacturer, without being degraded.
Strain	Unit change due to force in size of body relative to its original size.
Stress	Force exerted per unit area at a point within a plane.
Stress-cycles (SN) curve	Curve, allowing the resistance of the material to be seen, which indicates the relationship observed experimentally between the service life N and maximum stress S.
Stress relaxation	Stress relaxation occurs when a high stress is present that is relieved over time; the stress is relaxed with a subsequent reduction in the bolt's preload. The only way to minimise the effects of stress relaxation is to use materials that have an adequate resistance to it at the product's operating temperature. The effect of bolt stress relaxation is to reduce the clamp force provided by the bolts.
Stress-strain diagram	A diagram in which corresponding values of stress and strain are plotted against each other.
Structural bond	A bond, which is capable of sustaining in a structure, a specified strength level under a combination of stresses for a specified time.
Substrate	An adherend, a material upon which an adhesive is applied.
Surface preparation (or pre-treatment)	Physical and/or chemical treatments applied to adherends to render them suitable or more suitable for adhesive bonding.
Tack	The property of an adhesive that enables it to form a bond of measurable strength immediately after adhesive and adherend are brought into contact under low pressure.

Term	Definition
Tension	Mode of application of a tensile force normal to the plane of a joint between rigid adherends and uniformly distributed over the whole area of the bond-line.
Thermoset	A resin that is substantially infusible and insoluble after being cured.
Thermoplastic	A material that can be repeatedly softened by heating.
Traveller	A test specimen used for example to measure moisture content as a result of conditioning.
Viscosity	Resistance of a liquid material to flow.
Wet strength	Strength of an adhesive bond determined immediately after removal from a liquid in which it has immersed under specified conditions.
Wetting	A surface is considered completely wet by a liquid if the contact angle is zero, and incompletely wet if the contact angle has a finite value.
Yield strain	The strain, below which a material acts in an elastic manner, and above which it begins to exhibit permanent deformation.
Yield stress	The stress (either normal or shear) at which a marked increase in deformation occurs without an increase in load.

APPENDIX 2: STANDARDS

Summary of common test methods related to composite joints. See section 9 Testing and Standards. These standards are constantly being updated so it is important to check that the most recent version is being used.

Standard	Title
BS EN ISO 62:2008	Plastics. Determination of water absorption.
BS EN ISO 175:2010	Plastics. Methods of test for the determination of the effects of immersion in liquid chemicals.
BS EN ISO 291:2008	Plastics. Standard atmospheres for conditioning and testing.
BS EN ISO 899-1:2017	Plastics. Determination of creep behaviour. Tensile creep.
BS EN 923:2015	Adhesives. Terms and definitions.
BS EN 1465:2009	Adhesives. Determination of tensile lap-shear strength of bonded assemblies.
BS EN 6037:2015	Aerospace series. Fibre reinforced plastics. Test method. Determination of bearing strength.
BS ISO 6721-4:2019	Plastics. Determination of dynamic mechanical properties. Tensile vibration. Non-resonance method.
BS EN ISO 9142:2003	Adhesives. Guide to the selection of standard laboratory ageing conditions for testing bonded joints.
BS EN ISO 9664:1995	Adhesives. Test methods for fatigue properties of structural adhesives in tensile shear.
BS ISO 11003-2:2019	Adhesives. Determination of shear behaviour of structural adhesives. Tensile test method using thick adherends.
BS EN ISO 11357 (various parts)	Plastics. Differential scanning calorimetry (DSC).
BS ISO 12815:2013	Fibre-reinforced plastic composites. Determination of plain-pin bearing strength.
BS ISO 12817:2013	Fibre-reinforced plastic composites. Determination of open-hole compression strength.
BS EN 14364:2006 +A1:2008	Plastics piping systems for drainage and sewerage with or without pressure. Glass-reinforced thermosetting plastics (GRP) based on unsaturated polyester resin (UP). Specifications for pipes, fittings and joints
BS ISO 16237:2015	Mechanical joining. Destructive testing of joints. Specimen dimensions and test procedure for cross-tension testing of single joints.

Standard	Title
ISO 17212:2012	Structural adhesives. Guidelines for the surface preparation of metals and plastics prior to adhesive bonding
BS ISO 25217:2009	Adhesives. Determination of the mode 1 adhesive fracture energy of structural adhesive joints using double cantilever beam and tapered double cantilever beam specimens.
ASTM D1002-10(2019)	Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal).
ASTM D3163-01(2014)	Standard Test Method for Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading.
ASTM D3165-07(2014)	Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies.
ASTM D3433-99(2012)	Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints.
ASTM D3528-96(2016)	Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading.
ASTM D4896-01(2016)	Standard Guide for Use of Adhesive-Bonded Single Lap-Joint Specimen Test Results.
ASTM D5573-99(2019)	Standard Practice for Classifying Failure Modes in Fiber-Reinforced-Plastic (FRP) Joints.
ASTM D5656-10(2017)	Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading.
ASTM D5766 / D5766M-11(2018)	Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates.
ASTM D5961 / D5961M-17	Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates.
ASTM D6484 / D6484M-14	Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates.
ASTM D6742 / D6742M-17	Standard Practice for Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates.
ASTM D6873 / D6873M-17	Standard Practice for Bearing Fatigue Response of Polymer Matrix Composite Laminates.
ASTM D7248 / D7248M-12(2017)	Standard Test Method for Bearing/Bypass Interaction Response of Polymer Matrix Composite Laminates Using 2-Fastener Specimens.

Standard	Title
ASTM D7332 / D7332M-16	Standard Test Method for Measuring the Fastener Pull-Through Resistance of a Fiber-Reinforced Polymer Matrix Composite.

APPENDIX 3: JOINING DESIGN GUIDES

This guide does not set out to provide detailed design information for joining composites. However, a few useful design guideline documents are provided in Table 9. Expert advice should be sought when designing critical joints in composite structures. Each industry sector may have its own specific codes and regulations relating to composite materials and joints. Therefore, it cannot be assumed that designs will necessarily be transferable between applications.

Table 9. Selection of design guidelines and useful references for designing composite joints. Those marked * are free resources.

Guideline	Summary
Design Requirements for Bonded and Bolted Composite Structures * Broughton et al, National Physical Laboratory (NPL), 2002 [71]	Detailed design information for composite bonded and bolted joints (does not cover welded joints).
ESA Structural Materials Handbook ECSS-E-HB-32-20 * European Space Agency, 2011 [72]	Design and application guidance for polymer-based composites used for space structures. Data provided for materials appropriate for space applications. Published in 8 Parts.
Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook Clarke, CRC Press, 1996 [73]	Provides design rules and guidance for the structural design of buildings and civil engineering applications specifically using glass-fibre reinforced polymer composites. Covers the requirements for resistance, serviceability and durability of structures.
CMH-17-3G, Composite Materials Handbook Volume 3, Polymer matrix composites: materials usage, design, and analysis SAE International, 2017 [74]	Provides guidelines and material properties for polymer matrix composite materials mainly focussing on aerospace applications. Represents a compilation of relevant composites design, manufacture and analysis experience of engineers in industry, government and academia.
Composites Engineering Handbook Mallick, Marcel Dekker Inc, 1997 [75]	Offers information on the fundamental principles, processes, methods and procedures related to fibre-reinforced composites; presents a comparative view, and provides design properties of polymeric, metal, ceramic and cement matrix composites; gives current test methods, joining techniques and design methodologies.

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[71] Broughton, W.R., Crocker, L.E., Gower, M.R.L., 'Design Requirements for Bonded and Bolted Composite Structures', NPL Report MATC(A)65, 2002. http://eprintspublications.npl.co.uk/2130/ [Accessed 3/1/20]

[72] ECSS-E-HB-32-20 'Structural materials handbook', European Space Agency, 20 March 2011. https://ecss.nl/hbs/published-hbs-on-line/active-engineering-handbooks/ [Accessed 3/1/20]

[73] Clarke J L, 1996: 'Structural Design of Polymer Composites: EUROCOMP Design Code and Hand-book'. Chapman and Hall, London, 1996, ISBN 978-0-4191-9450-7. https://www.crcpress.com/Structural-Design-of-Polymer-Composites-Eurocomp-Design-Code-and-Background/Clarke/p/book/9780419194507 [Accessed 3/1/20]

[74] 'Composite Materials Handbook' Volume 3 - Revision G, SAE International, 2012, ISBN 978-0-7680-7813-8 https://www.sae.org/publications/books/content/r-424/ [Accessed 3/1/20]

[75] Mallick, 1997: 'Composites Engineering Handbook'. Edited by Mallick, P.K., Marcel Dekker, 1997, ISBN 978-0-8247-9304-3. https://www.crcpress.com/Composites-Engineering-Handbook/Mallick/p/book/9780824793043 [Accessed 3/1/20]

CS-25 - Large Aeroplanes * European Union Aviation Safety Agency[76] or FAR-25 / 14CFR Part 25 * Federal Aviation Authority [77]	Detailed and comprehensive aviation requirements aimed at minimising Type Certification problems. Details an acceptable basis for showing compliance with airworthiness codes. Does not include design guidance.
Aluminum Design Manual The Aluminum Association, 2015[78]	Provides design information for determining the strength of aluminium structural components, safety and resistance factors for aluminium building and bridge structures, fatigue resistance (especially mechanically fastened connections), adhesive bonded joints, sandwich panels and beams, etc
Assessment of Predictive Analysis for Bonded and Bolted T-Joints * Broughton et al, NPL, 2004 [79]	Research conducted at NPL into developing models and test methods for accurately determining deformation and failure in bonded and bolted structures under static and cyclic loading conditions

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[76] 'CS-25 - Large Aeroplanes', European Union Aviation Safety Agency. https://www.easa.europa.eu/certification-specifications/cs-25-large-aeroplanes [Accessed 3/1/20]

[77] FAR-25 / 14CFR Part 25, Federal Aviation Authority. https://www.ecfr.gov/cgi-bin/text-idx?node=14:1.0.1.3.11 [Accessed 3/1/20]

[78] 'Aluminum Design Manual 2015', The Aluminum Association, 2015 https://www.aluminum.org/aluminum-design-manual-2015 [Accessed 3/2/20]

[79] Broughton W R, Crocker L E, Gower M R L and Shaw R M, 2004: 'Assessment of predictive analysis for bonded and bolted T-joints'. NPL Report. DEPC-MPR 002. http://eprintspublications.npl.co.uk/2972 [Accessed 3/1/20]