National Composites Network

Best Practice Guide

Repair of Fibre Reinforced Polymer Structures

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Repair of Fibre Reinforced Polymer (FRP) Structures

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[1] For information on NetComposites, visit http://www.netcomposites.com/

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Repair of Fibre Reinforced Polymer (FRP) Structures

Introduction

Fibre reinforced polymer (FRP) materials are designed to get the best performance for a particular situation, and their ability to be maintained, replaced or repaired to a verifiable standard is of prime importance. However, a wide range of defects can occur when a FRP structure is damaged or when an unsatisfactory repair is completed, some evident on the surface, but most hidden.

The overall objectives of this best practice guide are:

- To review the current status of repair techniques
- To identify preferred repair procedures
- To identify test methods for assessing the strength of repairs

It covers state of the art repair techniques which have been identified from a technical literature review undertaken using existing published works, procedures, databases and the internet. It presents an overview of FRP repair and inspection techniques that exist throughout most sectors of industry, how the skills are implemented, how repair quality is maintained and what new technologies are under development. A wide range of repair issues have been covered, including detailed repair techniques and test methods currently used to assess the performance of repairs to FRP structures.

Acknowledgement is given to Heatcon Abaris Training for supplying images 1, 2, 3a, 3b, 4, 5 and 6

NCN Best Practice Guide - Repair of Fibre Reinforced Polymer (FRP) Structures

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1. THE NEED TO REPAIR

The growth in the use and application of FRP materials in world-wide industry is dependent on a number of major factors that include: basic raw material costs; ease of processing and finishing; environmental impact; structural performance; life expectancy; and reparability.

When an FRP product is designed, materials are selected that will satisfy specified performance requirements and can be incorporated into a functional structure or assembly. The shape will normally have been designed to meet known structural requirements and then, secondly, desired aesthetics. The product will continue to function satisfactorily until damage occurs due to material breakdown from wear, fatigue, external impact, or misuse [1-4]; then the decision to repair or replace is taken. If it is a low cost and easily disassembled item then direct replacement does not pose a problem, this being the case in some cosmetic non-structural uses of FRPs. However, many replacement parts are very expensive, and so repair must be an option to make a product viable in a service situation. Industry as a whole is also used to repairing metal structures through welding, bonding, bolting, riveting.etc, so there are expectations for FRPs to be satisfactorily repaired in a similar manner. As a result repair procedures have been developed.

2. DAMAGE ASSESSMENT

Damage to FRPs is often hidden to the eye. Where a metal structure will show a dent after being damaged, an FRP structure may show no visible signs of damage, and yet may have delaminated plies or other damage within.

Impact energy affects the visibility, as well as the severity, of damage in FRP structures. High and medium energy impacts, while severe, are easy to detect. Low energy impacts can easily cause “hidden” damage.

There are a variety of non-destructive inspection techniques available to help determine the extent and degree of damage [5]. Each has its own strengths and weaknesses, and more than one method may be needed to produce the exact damage assessment required. Table 1 provides a basic comparison between the non-destructive inspection techniques. For details of the techniques see the NCN Best Practice Guide on non-destructive testing (NDT) techniques. '1' indicates damage where the technique scores well, and '3' indicates damage where the technique is not so good.

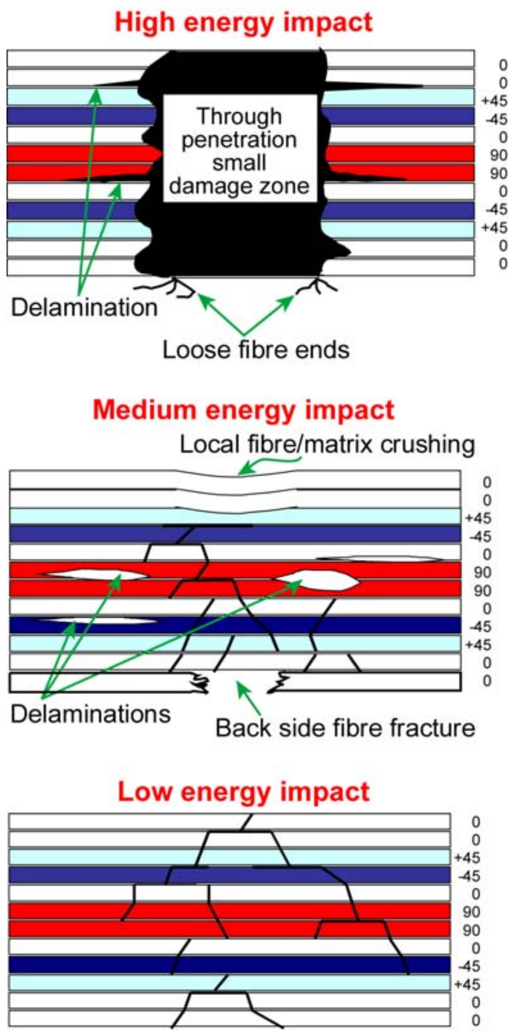

Figure 1: Levels of damage
Photo courtesy Abaris Training [6]

	Visual	*Tap test*	*A-scan*	*C-scan*	*X-rays*	*Thermal*	*Dye*
Surface delamination	2	1	2	1	2	1	n/a
Deep delamination	n/a	3	1	1	2	2	n/a
Full disbond	2	3	1	1	3	1	n/a
Kissing disbond	n/a	3	3	3	n/a	n/a	n/a
Core damage	2	2	3	1	1	2	n/a
Inclusions	2	2	1	1	1	1	n/a
Porosity	2	n/a	2	1	n/a	n/a	2
Voids	2	2	2	2	2	2	2
Backing film	n/a	2	2	2	2	2	n/a
Edge damage	1	2	2	1	1	2	1
Heat damage	2	2	2	2	n/a	2	n/a
Severe impact	1	1	1	1	3	1	1
Medium impact	1	1	1	1	n/a	3	3
Minor impact	3	3	3	3	n/a	3	n/a
Uneven bond line	3	n/a	3	3	3	3	n/a
Weak bond	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Water in core	n/a	2	3	1	2	1	n/a

Table 1: Suitability of damage assessment techniques [5]

2.1 Damage removal

The first step is to remove paint and/or outer coatings [5]. Chemical paint strippers must not be used, unless they are specifically designed for FRP structures. Most paint strippers are based on methylene chloride, which will attack cured epoxy resin (which is a common basis, or matrix material, for FRP structures). Paint and coatings may be removed by:

- Hand sanding without sanding through any fibres of the undamaged structure
- Wheat starch blasting
- Careful grit blasting or plastic media blasting.

It is important to check any repair manuals (such as structural repair manuals for aircraft) or guidelines offered by manufacturers and also to make sure all health and safety requirements are met.

After paint removal, additional damage assessment is performed, as hidden damage now becomes more apparent. Damaged FRP skin may be removed by careful routing or grinding through the damaged surface. Note the following guidelines:

- Routing is usually the method of choice for a solid laminate with through thickness damage. However, for a thick solid laminate with damage only on surface plies, use careful sanding until undamaged plies are reached.
- Routing also works well for a sandwich structure with damage into the core. Damaged cores should also be removed and can be routed out or cut and scraped out using a knife or other cutting tool.
- Remove damage in circular or oval shapes, and do not use sharp corners. If an irregular shape must be used, then round off each corner to as large a radius as practical.

2.2 Contamination

Damaged FRP structures may be contaminated by fuel, oil, hydraulic fluid, etc [5]. Damaged areas may also absorb moisture, which will prevent a successful repair being made. Solid laminates contaminated with fuel, oil, etc. may be treated by wiping thoroughly with a solvent, using reagent grade solvents for the final wipe. It is important to know what the structure is made of, what the contaminant is, and to check any and all suggested procedures to ensure the solvent being used is capable of dissolving the foreign fluid without further damaging the FRP structure.

If the core in a sandwich structure is contaminated, replacement of the affected material is advisable. Solvent cleaning may be possible via a vapour degreasing process.

All affected FRP materials must be dried before an effective repair can be achieved. Cured resin as well as fibres will absorb moisture from the environment, and honeycomb cores can hold large quantities of fluid. If performing a repair using high-temperature curing resin or prepreg, all moisture must be removed to prevent steam from forming and disbonding the repair. When repairing a structure with honeycomb core, the core is almost always contaminated.

2.3 Water break test

The water break test is used on FRP surfaces to check that no contamination remains and that the surface is in an acceptable condition for a repair to be carried out. In the test, water is sprayed on to the prepared surface and should remain in a continuous film over the whole area for at least 30 seconds [7, 8]. If water separates into droplets or the film is not continuous, then the cleaning operation has to be repeated until this requirement is met. The surface needs to then be thoroughly dried before repair is carried out.

3. REPAIR PROCEDURES

There are many formalised repair procedures prepared by reputable organisations throughout the world, all evolved from good historical industry practice and adapted to the specific conditions of each sector.

All successful repairs carried out to any substrate rely on skilled repair technicians, good surface preparation, well designed repair procedures and the use of first rate materials. They also depend on stringent quality control encompassing reliable damage detection, surface cleanliness and texturing examination, drying to known limits, undertaking work within permitted temperature and humidity envelopes, and controlling resin cure to manufacturers' recommendations. This should be followed by NDT inspection of the finished repair or destructive testing of sample coupons or bars.

Each industry sector has set its own standards for quality control of repair procedures, structural repairs of aircraft being the most demanding. There is strong evidence to suggest that when repair procedures are prepared, each industry works closely with the same resin and fibre reinforcement raw material producers, but the resultant quality control requirements issued to the on-site operators often varies widely. The EuroComp design code specifies the best practice for adhesively bonded joints in FRP materials and should also be consulted when designing repairs in jointed structures [9]. Attention should be drawn to the skills required to effect bolted repairs, often to primary structures; it is important they are undertaken properly, but it is often not realised how difficult FRPs are to drill cleanly and accurately.

It has already been stated that a good adhesive joint relies on good surface preparation, appropriate quality materials and an ideal working envelope. Mechanical abrasion of the polymeric surface and solvent degreasing appears to be the universal industrial approach to surface conditioning of thermoset FRPs prior to bonding, whilst thermoplastic FRPs use a more scientific approach.

Research has identified the likely causes for bond strength reduction, but confirmed that significant lap shear strength improvements could be achieved over untreated FRPs by most surface treatment methods [10, 11]. Established surface activation techniques such as: corona discharge; flame treatment [12]; chemical etching; alumina grit blasting; silicon carbide abrasion; cryogenic blasting; and sodium bicarbonate blasting all provided the expected improvements. Grit blasting imparted the least benefit and cryogenic blasting the least fibre damage.

In spite of the joint strength improvements possible by changing the surface energy exhibited by polymeric materials to assist adhesive bonding, many thermoplastic parts continue to be repaired by various forms of welding. Any reinforcement content at the joint will, however, inhibit the resultant weld strength and cause porosity.

3.1 General Repair Guidelines

The quality of any repair is dependent not only on the materials used and skill of the operator but also on the environment in which the repair is carried out. Temperature, humidity, and cleanliness are important factors in creating the optimum envelope for production of the best repair.

Damage usually occurs to FRP structures when they are in service and where repair facilities are not readily available, be they chemical vessels, bridges, buildings, ships, motor vehicles, or aircraft. A decision needs to be made whether the repair can be carried out in-situ due to position, size or complexity of the overall structure or whether the part can be removed for repair in a controlled workshop.

Once the extent and seriousness of damage has been assessed a decision can be made on how quickly it needs to be repaired. It is the additional costs that surround a repair that affects how a repair should be undertaken. For example, when a scheduled civil passenger aircraft is forced out of service due to an unacceptable damage report, its grounded costs are exorbitant whilst it is awaiting urgent maintenance, as it is only earning money when flying. A building or bridge may need to be closed whilst repair teams move into action, often necessitating movement of the occupants or extensive highway traffic management activity. These additional servicing requirements can increase project costs by tens of thousands of pounds for every day the repair takes. Conversely, it is accepted that a motor vehicle would be returned to a garage for rectification and a loan vehicle provided whilst it was off the road.

If it is imperative that a repair is carried out immediately to prevent further damage, then a controlled work area must be made available to provide either a temporary or permanent solution.

If outside, then a localised repair cell needs to be set up around the damaged area, isolating it from the prevailing weather conditions. This can be achieved using sheeting and adhesive tapes to form a tent, and temperature control. The main considerations when setting and operating a localised repair cell are:

- The area created should be made free of dust, soot, fibrous materials other than specified reinforcements, oils, fumes and gases.
- Protective equipment should always be provided to the operator in the form of gloves and masks to prevent contamination of prepared repair areas and minimise personnel health risks.
- If toxic fumes are likely to be emitted from cleaning solvents, resin diluents etc. during repair procedures then provision must be made to safely remove these without causing risk to the operator or prepared environment, i.e. extraction airflow can chill heated areas.
- Basic services such as compressed air, electricity, water, and vacuum must be made available for standard repair and test equipment to function.

A typical repair procedure takes the following steps:

- Establish the extent of the damage and assess whether part is repairable
  - Visual techniques for external damage
  - NDT techniques for internal damage
  - Rebuild or replace if too damaged.

- Establish the type of damage e.g. moisture, ingress, disbond, delamination, etc.

- Cut out and remove all damaged material until only sound laminate remains (if the surface has a protective coating, such as paint, this must be cut back to create an area 20mm from edge of the hole). When the surface damage has been removed, check for continuing defective areas and finally check that the action of removing the damage has not created new damage

- Decide on the repair technique to be used

- Thoroughly clean, degrease, and ideally carry out a 'water break test' [7]

- Thoroughly dry the damaged laminate and prepared areas

- Select materials for the repair: They all need to be fresh, within their shelf life and at working temperatures

- Weigh out the resin proportions to ensure correct fibre volumes for retention of structural properties, if using 'wet lay'

- Cut reinforcement patches to the sizes needed (exact or overlap) and orientation

- Prepare the laminating and curing equipment
-
- Carry out the repair to 'best practice' ensuring no processing defects occur

- Monitor the cure cycle and environmental envelope to enable certification of repair

- Inspect the finished repair and certify.

3.2 FRP Repair Styles

3.2.1 Patch

The most common repair carried out on all types of FRP is the patch repair. It is a simple and low cost technique that needs the least preparation. It is also functional, fast to carry out and is ideal for urgent ‘field repairs’, but can be unsightly, bulky and of limited strength.

The patch repair can be temporary or permanent, depending on the application, and is usually applied by wet lay-up techniques. Figure 2 shows a typical repair configuration. It is not essential for the damage to be cleanly cut away, but the contact surface should be flat, abraded and degreased [13]. It is also possible to use the patch to improve the strength of existing undamaged structures, enabling them to support higher loadings [14-16], or to easily overcome identified design weaknesses in a structure.

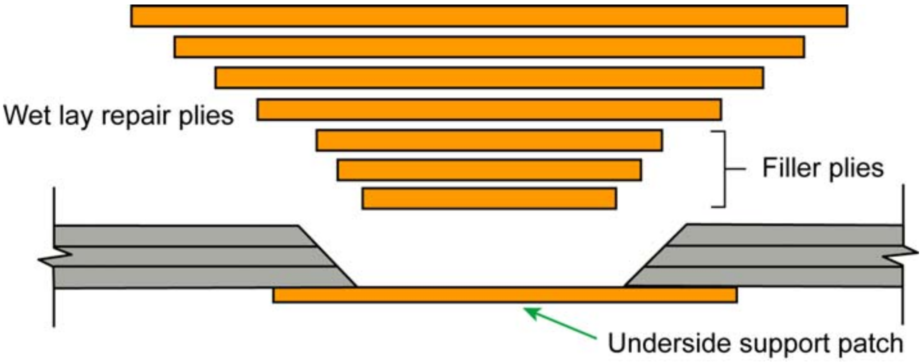

Figure 2: Laminated Patch Repair

3.2.2 Scarf Joint Repair

Scarf joint repair is favoured for strength-critical applications, and where it is necessary to restore a surface’s aerodynamic or hydrodynamic profile. Figures 3a and 3b show the different preparation styles used. Scarf repairs often use a 50:1 taper ratio for best results, and therefore remove much more good material than lap or patch repairs. They should only be used when specified by the manufacturer and when good workshop conditions and trained staff are available.

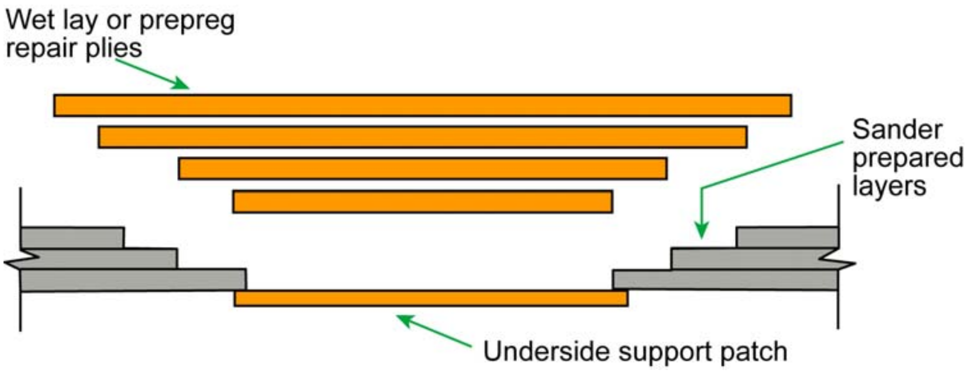

Figure 3a: Stepped Scarf Repair

This type of joint can reliably restore 90% of the original strength of the undamaged material, and is specified in most aircraft repair manuals [17, 18]. Either wet resin lay or prepreg materials can be used. Preparation of the bond line is critical and is usually carried out carefully using power tools with routers or abrasive disks, as the tapered scarf can have a slope of between 20:1 and 50:1, depending on the material type, lay up, and adhesive used.

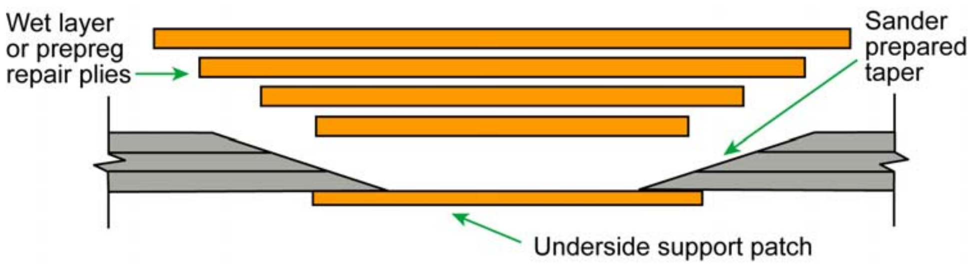

Figure 3b: Tapered Scarf Repair

Repair procedures are usually designed to achieve a scarf shear strength approximating to twice the tensile strength of the present material. Fibre damage to remaining material around the scarf during abrading must be minimised to ensure further weakening of the laminate's construction does not occur, so operator skill is high and the attention to detail required make this technique the most expensive to undertake.

In addition, to consolidate the repair, both vacuum bagging and controlled heat cure equipment is required and the end result is a quality certifiable repair that is favoured by the aerospace industry.

3.2.3 Pre-Cured Doubler

This technique has been developed by the aerospace industry as an attempt to minimise the out of service delays that keep planes from flying [19, 20].
The doubler, Figure 4, is a pre-cured 'plaster' that has been designed and manufactured by mass production in a controlled FRP manufacturing facility. It has a number of specified uses as either an emergency temporary repair to prevent damage worsening or as a permanent solution to minor damage. It is basically a controlled performance patch that uses separate structural adhesives to match each different application, while its perforated design ensures maximum peel resistance, even with minimum surface preparation.

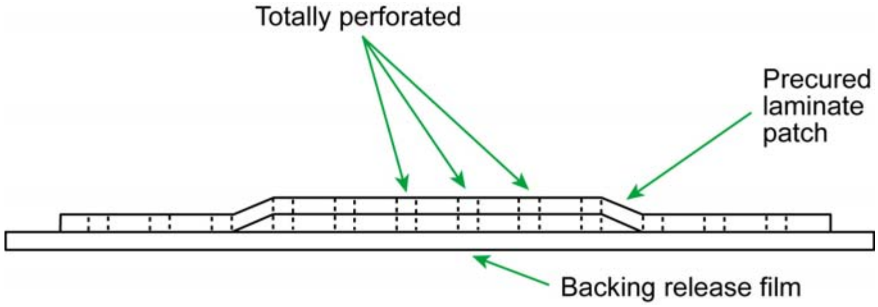

Figure 4 - Adhesive Bonded Doubler

3.2.4 Plug

Plug repairs were developed to mend holes in ships using wood, wadding and pitch.

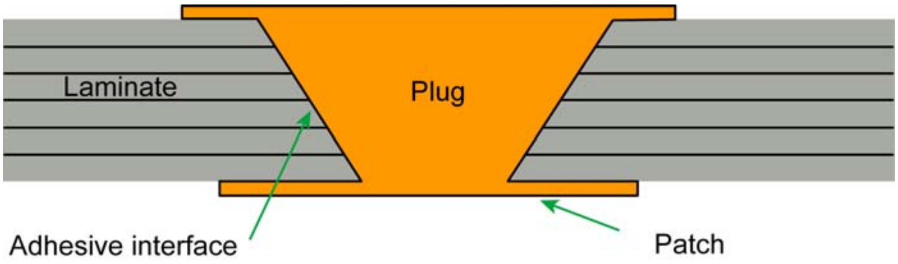

Figure 5 - Adhesive Bonded Plug Repair

The application of the technique to modern day FRPs is not dissimilar; machine tapered plugs are secured in a roughly prepared hole with an ample coating of adhesive. The repair is relatively fast and inexpensive to complete, but has limited strength, due to discontinuity of reinforcement and uneven adhesive film thickness. A precision, machined hole is required for maximum strength and the size of damage repairable this way is limited to the availability of plugs, so is less favoured than the patch repair.

3.2.5 Bolted Plates

Bolted plates, as alternative to the plug or patch repair, are commonplace in aircraft and marine industries and much research has taken place into their use with FRP materials. The main advantages are that they require few resources such as material storage or cure equipment, can be fitted by unskilled personnel, offering simplicity and reliability in the field, which is often not available with bonded repairs. However, problems can be encountered with both bolt over-tightening and creation of fixing holes causing further damage to the structure. Preparation of the area to be repaired must be undertaken by suitably trained staff to prevent further damage due to drill wander or inner surface breakaway and to ensure inner surfaces such as fuel cells are not penetrated.

DEFECTS	**REPAIR TYPES**				
	Glass Fibre Laminate			**Carbon Fibre Laminate**	
	Vinyl Ester Scrimp[22]	***Polyester Hand Lay***	***Vinyl Ester Sandwich***	***Epoxy Prepreg Monolithic***	***Epoxy Prepreg Sandwich***
Dry Patch	Resin Infusion	Resin Infusion or Scarf	Patch or Scarf	Resin Infusion or Scarf	Patch, Doubler or Scarf
Surface Gouge	Fill or Patch	Fill or Patch	Fill or Patch	Fill or Patch	Fill or Patch
Delamination	Resin Infusion or Scarf	Resin Infusion or Scarf	Patch or Scarf	Resin Infusion, Patch or Scarf	Patch or Scarf

Moisture Ingress	Resin Infusion or Scarf	Patch or Scarf	Patch or Scarf	Patch or Scarf	Patch or Scarf
Edge Disbond	Resin Infusion	Resin Infusion	Resin Infusion	Resin Infusion	Resin Infusion
Bond Failure	Resin Infusion or Scarf	Resin Infusion or Scarf	Scarf	Resin Infusion or Scarf	Scarf
Foreign Inclusion	Assess Effect	Assess Effect	Assess Effect	Assess Effect	Assess Effect
Fibre Breakage	Replace or Scarf	Replace or Scarf	Replace or Scarf	Replace or Scarf	Replace or Scarf

Table 2: Typical defects and repair approach [21]

3.2.6 Resin Infusion or Injection Repair

This technique restores the original part to near-design compressive and shear strength through injecting low viscosity adhesive into a delaminated structure, through the use of vacuum to re-bond the ply surfaces together, thus consolidating the structure until resin cure is complete. This method is used in both aircraft repair [21] and marine applications as a production (SCRIMP - Seemann Composites Resin Infusion Moulding Process) [22] and repair system (RIFT – resin infusion under flexible tooling).

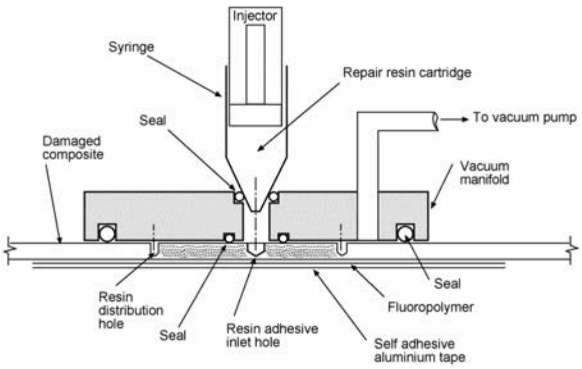

Figure 6 - Resin Infusion or Injection Repair

It is a fast, inexpensive and popular repair that eliminates the need for careful surface preparation, and can be undertaken in-situ with or without vacuum evacuation assistance. However, where internal surface contamination has occurred (due to oil leakage etc.), the fracture surfaces need flushing with degreasing agent and drying prior to resin injection. Also, if there is a continued risk of contamination, then injection repairs should either be avoided or extra surface protection provided.

3.3 Industry-Specific Repair Techniques

Each industry addresses the problems of repair in a slightly different way, but the principles are very similar.

To summarise, the current applications of repair techniques identified are:

- ***Automotive and Rail***

Major: Replace with new
Minor: Hand laminate patch with Chopped Strand Mat (CSM)

- ***Chemical, including pipes***
  Major: Replace with new
  Minor: Hand laminate patch or plug with CSM/woven fabric, epoxy

- ***Construction***
  Major: Replace structure
  Minor: Laminate patch with woven fabric
  Strengthening: Bonded pultrusion

- ***Marine***
  Major: Replace or repair scarf or RIFT
  Minor: Repair temporarily or permanent, hand laminate woven cloth patch

- ***Aerospace***
  Major: Replace or repair
  Minor: Temporarily - patch or doubler
  Permanent – scarf

- ***Wind turbine blades***
  Major: Replace with new
  Minor: Repair temporarily or permanent, scarf or patch

3.3.1 Automotive Industry

Generally the repairs done to motor cars, trucks, and other vehicles constructed from FRP materials are cosmetic rather than structural. The use of FRPs by automotive Original Equipment Manufacturers (OEMs) tends to be for hang-on parts such as closure and body panels, roofs and floors rather than as structural parts. Often due to time and cost restrictions, parts are replaced rather than repaired. Currently, major FRP vehicle producers have confirmed that they generally cut away major damage and replace with new sections.

When repairs are carried out, it is to manufacturers' guidelines only, by non- or semi-skilled personnel who perform repairs that are basically weatherproof or aesthetically pleasing [24]. Where structural parts are damaged they are generally replaced with new, but when vehicle damage occurs in a road accident, GRP clad vehicles are usually returned to the original manufacturers for controlled repairs. Because the market size is quite small compared to steel bodied vehicles the infrastructure does not exist to allow critical repairs to be carried out by agents.

- Materials used tend to be glass fibre chopped - strand mats (CSMs), or woven cloths that are wet laid-up using cold cure polyester or phenolic resins and finished with heavily loaded body filler compounds

- Damaged areas are cut back, cleaned, abraded, and brushed with solvent followed by a laminating resin or adhesive

- The structure is rebuilt using sufficient reinforcement layers as specified by the manufacturers with minimal resin, rolled to exclude air bubbles, and allowed to cure

- Part surface is ground flush to the appropriate curvature with abrasive disc tools, and hand finished. Paint or other protective surface is then applied to hide the repair, match the original surface, and protect it from weathering

Typical repair designs used: Scarf, Plug, and Patch.

3.3.2 Chemical Industry

The chemical industry utilises FRPs in the manufacture of pipes, valves, pressure vessels, and tanks. FRPs have replaced metal, ceramic, and rubber items due to the excellent chemical attack resistance of resins and fibres used in their manufacture, ease of transportation and installation and the design freedom afforded by modern manufacturing techniques.

Due to the nature of the chemicals being processed or stored most parts are designed to satisfy high safety-factor structural specifications. Should parts become damaged by impact or earth movement they would either be replaced or patch repaired depending on the criticality of the application.

The main materials used are glass-reinforced polyester, vinyl ester, epoxy, furane or phenolic, generally with resin rich surfaces on the working face for maximum corrosion resistance. The working procedures indicated in BS 4994: ‘Design and construction of vessels and tanks in reinforced plastics’ highlight the attention to detail required for this industry. Allowances are often made at the design stage for damaged parts to remain in functional service at either reduced working pressures or with an acceptable controlled leakage. Depending on the application, this could be on a continual basis, until a replacement part was installed or an in-situ over laminated repair effected [25].

Typical Repair Designs used: Internal or External Patch, Plug, Scarf, or Bolted/Gasketed Plates.

3.3.3 Construction Industry

FRPs are becoming more prominent in the construction industry as experience-based structural design data becomes more readily available. Architects can incorporate fibre reinforcements to extend the performance of buildings and structures to cope with climatic changes and geological movements. For example, FRP materials are widely used in building reinforcement in seismic zones. Though primarily used in new projects in the form of structural members, roofing, and cladding, high performance carbon and glass fibre composites are now used for repair of damaged concrete, timber, masonry and steel structures.

Bridge supports, piers, motorway sections etc. that have become weakened due to forceful external damage, weathering or internal corrosion can be satisfactorily reinforced. This is done either by the external structural adhesive bonding of pultruded carbon fibre strips or plates, or by wrapping (hand laminating) additional layers of fibre reinforced material over the damaged areas, restoring them to original or higher compressive strength and providing improved weather protection [26, 27].

The other main applications for externally bonded structural profiles are damage prevention, by strengthening floors in existing buildings to support higher loads, to provide increased flexural strength to bridge superstructures, and sealing defects caused by water ingress into the structure of pre-cast sectional buildings.

FRP repair and stiffening materials have successfully replaced steel-based reinforcing systems despite FRPs costing more than metals. Applications that used this new approach have shown that substantial cost savings can be achieved on the overall contracts, as transportation, handling, lifting, securing, installation, and maintenance costs are all minimised due to the high strength to weight ratio of composites. The market is growing rapidly as more towns in earthquake regions endeavour to protect existing buildings from the effects of shock waves. Although much of the application activity occurs in countries in earthquake regions such as, Europe's buildings and bridges are gaining the benefit of FRP structural repair systems [27, 28].

Many repairs are carried out ideally under carefully controlled climatic conditions, and preparation of bond line joints is critical to achieve maximum adhesion. The substrate surface must be blast cleaned to remove dirt or loose material, and create a key for adhesion promotion. Although it is ideal to have low moisture levels and operate in warm ambient temperatures this is rarely possible, so adhesive chemistry has been adapted for use in a wider environmental envelope using localised moisture (up to 5% maximum to assist the resin curing mechanism). To help repair contractors in the USA, resin manufacturers developed epoxy resins for pre-impregnated fibre mat applications that have shelf lives of up to a year without the need for special temperature controlled material storage equipment.

Typical Repair Design used: External Patch

3.3.4 Marine Industry

There has been a gradual change over the last forty years to the use of FRPs as a direct replacement for timber and metals in leisure, commercial and military vessels. As a result of the diverse specification improvements available from FRP construction, vessels have become more economical to build, operate and maintain. However, due to the nature of operation, vessels can easily become damaged by collision with piers, floating debris, other shipping, rocks and the repeated shock loading that occurs during bad weather.

Damage that occurs to marine FRP structures is similar to other applications. Skin puncture, moisture ingress, delamination, fibre crushing, and blistering are all common. Materials can also be aggravated by constant contact with seawater, often resulting in osmotic blistering which needs specialist rectification. Damage prevention measures can be incorporated into vessels by over-laminating retrofit improvements onto under-strength structures that have shown weaknesses in service.

Boat building is a less precise science than the aerospace industry where sophisticated design technology, automated fibre placing, autoclave cured prepreg laminates and 100% NDT of components are typical. Therefore, as manual hand lay-up composite construction is mainly used in boatyards, it is probable that more defects will occur due to the process and lower quality control standards.

Repair techniques are similar to other industries, with the one chosen being dependent on the structural nature and hydrodynamic specification of the damaged area. A patch, plug or bolted plate may be adequate as a temporary repair whilst afloat, but this must usually be retrofitted with a correctly prepared permanent repair later. This can be a prepared scarf joint with over-lamination on the inner face. These types of repair are carried out on racing yachts, pleasure craft, military vessels and lifeboats to enable them to remain in service [29, 30]. The scarf can be cut from the inside of the hull as access is usually possible from both sides of the boat. Typical scarf slopes are reported to be between 40-100:1, and there is usually a small scarf cut on the outside of the repair to allow for a build up of gel coat or paint on the outside of the repair material.

Another technique gaining acceptance for delaminated structures is resin infusion under local vacuum that pulls the separated layers together and adhesively bonds them. This technique is encompassed in a system termed RIFT - Resin Infusion under Flexible Tooling, which is also used to strengthen and repair steel infrastructures in civil, offshore and defence industries [31].

Typical Repair Designs are: Scarf, External Patch, Bolted Patch, or Resin Infusion.

3.3.5 Aerospace Industry

FRP materials are used extensively in military, civil and leisure aircraft, the latter allowing less critical repairs to be carried out in the field using preformed patches in conjunction with wet lay-up GRP. The use of high performance FRP materials in jet aircraft and helicopters stems from many years development. The wealth of design and performance data generated from the use of different materials and constructions has provided the industry with historical references to establish proven design and repair safety procedures. This has enabled specialist manufacturing and repair industries to operate throughout the world, working to procedures issued by the original aircraft manufacturers. Stringent quality control systems are in place, governed by independent organisations (CAA etc.) that ensure a sound quality repair of known performance is undertaken. The materials and equipment developed for damage detection, safe controlled repairing and inspection of aircraft structures rely on close attention to procedural detail. Aircraft designers and manufacturing companies specify:

- Which parts of a FRP structure can be repaired.
- How large a damaged area or how many individual pieces of damage in an area can be permitted to allow the part to be repairable.
- How many repairs can be permitted before a part has to be replaced.

At present only secondary structures within wings, tailplanes, fins and radomes are regularly refurbished following accidental impact damage or lightning strike, using a range of approved repair methods and appropriate materials.

These repairs are carried out by approved personnel working in controlled atmospheres, using moisture free pre-cured laminate patches (doublers); prepreg fibre reinforced systems, or controlled wet lay-up techniques using virgin fabrics that enable precise fibre volume fractions to be achieved. Following a temperature regulated resin cure, generally under vacuum, the resultant repair should satisfy the design specification of the original laminated part on inspection using non-destructive methods.

Every application is treated differently, but generally all repair procedures will follow aircraft Original Equipment Manufacturers (OEM) published recommendations that are written to achieve a full strength structural repair, and to minimise operator error [8, 31-37].

Typical Repair Designs are: Scarf, Stepped Scarf or Lap, Plug, and Patch.

3.3.6 Wind Turbine Industry

Although wind blades are built to last at least 20 years, lightning strikes, manufacturing defects, and damage during shipping all occur. As blades range from 29 feet to 200 feet in length, repair onsite is a cost-effective solution for generators and turbine manufacturers alike.

Scarf repair and the plug/patch method are suitable to repair holes and delamination defects on wind turbine blades. In both cases, the damaged laminate is cut out down to the depth of the deepest flaw and a repair scheme is applied. Scarf repairs are particularly suited to external repairs of the thick laminates found in wind turbine blade load carrying parts because of the unlimited thickness of material that can be joined and the smooth surface contour produced. Single-sided scarf patches can also be employed to repair part-through or full-penetration damage [38].

Typical Repair Designs are: scarf, plug and patch.

3.4 Health and safety procedures

All FRP repair procedures call for the use of processes, substances and/or procedures that may be injurious to health if adequate precautions are not taken. They refer only to technical suitability and in no way absolve the supplier or the user from statutory obligations relating to health and safety at any stage of manufacturing or use. Where attention is drawn to hazards, those quoted may not necessarily be exhaustive.

Materials used for the manufacture and/or repair of all FRPs are potentially dangerous and prior to use the manufacturer's data sheets must be read.

3.4 1 Safety Precautions

Damaged FRP materials may cause a number of health hazards. Single fibre particles, with a diameter of 3 to 4 microns and a length of less than 0.1 mm pose the greatest threat to the respiratory system. FRP material dust is injurious to health; therefore a face mask must be worn at all times when drilling or abrading the materials and dust must be removed through a vacuum system and disposed of properly as a hazardous material.

Goggles are essential for use in work involving machining or any operation where the likelihood of airborne fibres exists. Extreme care should be taken when preparing a repair site as damaged laminates contain rigid, razor sharp needles of resin coated fibre that can pierce the human body with ease. Hand, eye and body protection is strongly recommended.

Individual filaments are very brittle and broken fibres may cause irritation to the skin. Barrier creams should be used and protective clothing worn. If irritation is felt, thorough washing and rinsing helps to remove loose filaments.

Disposable polythene gloves or thin rubber gloves should be used (in addition to the barrier cream) when carrying out a repair, to keep resin deposits off the hands and barrier cream/natural skin oils off the degreased repair site.
Care must be taken not to contaminate the prepared surfaces when using barrier creams or protective gels.

4. MATERIAL FOR REPAIR

When damage occurs to any FRP part, it is either replaced with a new component or repaired with like-for-like materials specified by the original equipment manufacturer. The main exceptions are when repairs need to be undertaken to weaker substrates or to hot cure resin laminates. In the latter case, an adhesive resin of comparable mechanical properties is required that can be cured at a lower temperature than the original structure, ensuring that degradation of material in the surrounding structure does not occur.

As the range and properties of FRP materials is vast, and their storage and supply can be logistically difficult, many repair organisations are trying to unify and rationalise the materials and consumables used in completing the repair.

Repair resins tend to rely on formulations of epoxy or polyurethane chemistry, which offer excellent bond strength and toughness other materials often lack. However, where chemical or water resistance is of prime importance then other systems may be used, including polyester and vinyl ester, although most resins have a limited shelf life and need storing in a controlled temperature environment.

During mixing, processing, application and cure, flaws, inclusions and defects can occur that reduce both the adhesive and cohesive performance of the material, and imperfections of this nature can only be detected following thorough non-destructive inspection or by identifying deviations from laid down manufacturing procedures. The types of defects that occur and their causes are described below [Annex 2].

- ***Cracks***: due to high exotherm during cure, resin rich areas or poor mixing
- ***Porosity***: entrapped air during mixing or laminating
- ***Voids***: larger volume of entrapped air or foreign matter
- ***Disbond***: poor adhesion of resin to adherend, insufficient surface preparation in correct cure
- ***Delamination***: poor surface preparation, presence of moisture, poor mixing, in correct cure
- ***Poor Cure***: bad mixing, poor temperature control, wrong environmental envelope (which reduces the binding properties in the adhesive resin).

4.1 Resins for Repair

Resin systems move forward with advances in chemistry. Although many systems are repaired with similar chemistry, improvements in the performance of individual resins occur and, where quality control authority permits, deviation from the original specification should be encouraged. Generally, high performance epoxy systems are chosen for structural applications, but polyester, vinyl ester, and polyurethane resin based adhesive systems are also commonplace.

The use of alternative material specifications is not accepted by many industries, aerospace particularly. However, guidance committees such as the Commercial Aircraft Composite Repair Committee (CACRC) set up by groups of concerned authorities in this industry are attempting to direct the original equipment manufacturers to approve generic material types and related quality and performance specifications, rather than to approve only individual manufacturers’ products in FRP part development.

It is vital to select a compatible material for repair work. If a technical procedure does not state a preferred resin type then assumptions should not be made. The original part producer should be contacted for a recommendation or analysis carried out by a polymer materials expert to verify that a selected adhesive or resin meets the performance criteria and service conditions of the product.

FRP repairs are generally carried out using wet resin lay-up with dry fibre reinforcement, adhesive bonding of pre-cured FRP patches; resin impregnation to re-bond a fracture, or pre-resin impregnated fibre mat/ fabric systems adhered to a prepared repair site. The thermoset resins used suffer from a limited shelf life, often less than 12 months, necessitating holding stock at sub-zero temperatures. Carefully stored materials will provide their prime adhesive and structural capabilities during this ‘life’, but must be disposed of or re-graded for reduced structural performance characteristics once this period has ended.

The major material producers distribute their resins world wide, so obtaining a source of the correct type should not be difficult. However, sourcing a cost effective quantity to undertake single repairs will often be a problem as the sub-division of bulk quantities into small containers always incurs high charges.

The resin systems listed below are some of the most widely used but it should be noted that these form only a very small selection of the multitude of grades and types of repair resin/ reinforcement systems available throughout the world.

4.1.1 Epoxy Resin
These are extensively used in advanced structural FRP materials; epoxy resins complement polyesters as the most commonly used high performance resins. There is a wide choice of grades providing variation in mechanical performance, toughness, temperature resistance, and shrinkage. As a high performance resin, it has become accepted for the construction of air and space craft, racing cars, lightweight high speed boats, yachts and other surface vessels, in addition to industrial, chemical and electrical applications.

4.1.2 Polyester Resin
These are most widely used thermosetting resin for FRP manufacture, due to its low cost and ease of processing. The resin is popular for general commercial applications, including leisure products, tanks, sanitary ware and automotive accessories.

4.1.3 Vinyl Ester Resin
These are chemically very similar to polyester resins but with enhanced chemical and temperature resistance. Vinyl ester resins are less expensive than epoxy resins. They are used in automotive vehicle and marine vessel manufacture where higher service temperatures are expected, and in repair of vinyl ester and polyester GRP as a laminating or injection resin. Vinyl ester resins are used to fill internal voids, repair disbonded cores, bond internal delamination and to provide a high performance repair.

4.2 Fibre Reinforcements

The main types of material used in FRPs for structural applications are carbon, aramid (Kevlar or Twaron) and glass. The fibres are often pre-treated to enhance adhesion to specific resin chemistry, so selection of the correct type is very important.

Glass, carbon, or aramid fibres are generally used in the form of fabrics to reinforce FRP laminates. The advantage of using the reinforcement in this form is that it creates a well defined laminate, as the individual fibres are pre-secured in their intended orientation prior to consolidation in a resin matrix. Fabrics are used in dry form or as pre-impregnated sheet material, although they are more expensive than basic fibre rovings as they involve additional textile style processing after the production of the initial fibres. Different weave patterns are available offering variations in mechanical performance, fibre orientation and drapability that also allow ease of impregnation, wet out or resin flow.

There are generally three types of fabric:
- random oriented
- aligned fibre woven material
- aligned fibre non-woven (non-crimp/stitched)

and the style of material used for structural repairs is usually:
- Woven Roving (WR)
- Uni-directional Roving (UD)
- Chopped Strand Mat (CSM)

Chopped strand mat is only used in structural repairs where weight and aesthetics are not critical, as the nature of this material does not allow a high fibre volume content and is therefore wasteful of resin. It is the easiest material to use in an emergency patch repair via hand-lay techniques.

Uni-directional fabrics offer high strength in the warp (longitudinal) direction only, and these are held straight with very light weft (transverse) threads. These weft threads are only a few percent of the total fabric weight and provide no significant reinforcement.

Woven roving fabrics come in many forms. Plain weave is a simple weave pattern (over one under one) which produces large gaps between fibre tows and causes a high degree of fibre crimp. These characteristics limit the weight of fabric that can be produced in plain weave before the pattern must be altered. As many FRP laminates are multi-contoured in shape, it is essential that the fabric used can drape in order to obtain the best mechanical properties and this is achieved by varying the weave pattern. An alternative is twill weave, where one or more warp ends weave over and under two or more weft picks in a regular pattern, producing a straight or broken diagonal line in the fabric. It drapes, hangs and folds better than plain weave, being more pliable, and has better sewing characteristics than satin weave. Here each fibre passes ‘over several and then under one’. These fabrics are distinctive in that the bulk of warp fibres lie on one surface, whilst the bulk of weft fibres lie on the other. However, they are not symmetric about the centre plane, so additional care must be taken in design and fabrication to ensure a symmetric laminate is produced.

Ideally, the same material weave and weight should be used for repairs as was used for the original construction because the fibre tensile properties and modulus in a composite are affected by the weave style. If the identical material is not available, then consideration must be given to the strength and stiffness of the original material and whether additional layers may be necessary if only an inferior woven cloth is to hand. In this and all instances where alternative choices are to be made, expert guidance should be obtained from the material manufacturers.

Weave styles have been standardised to a large degree according to MIL (US Military) and aircraft manufacturers’ materials specifications. The SAE AIR 4844A Composite and Metal Bonding Glossary [7] is recommended for reference when looking at fibres and fabrics in more detail.

Carbon fibre is generally pre-classified by aerospace and marine design specifications for high performance structural use. The materials are expensive, so need to be used sparingly according to the appropriate design authority’s recommendation.

- Woven roving - These are available dry or in prepreg form from established carbon fibre processors.

- Pultruded strip - Sika Carbodur CFRP strips (pre-cured), used for over laminated patch repairs and strengthening.

- Pre-cured Doubler - BAE approved CFRP multidirectional plasters, thickness dependent on original laminate. Sourcing and size availability details can be obtained from BAE Systems and Airbus, Filton.

The use of aramid fibre in repair procedures is not common due to adhesion difficulties. For aramid FRP structures, the recommended repair procedure uses glass fibre layers over any damaged areas.

4.3 General guidance in choosing repair materials

In general, repair materials are similar to the original material, and are summarised as follows:

- Bonded repairs use thermoset or thermoplastic resins
- Dissimilar substrates based on thermoset use epoxy systems
- Lower cure temperature resins used to:
  - prevent damage to original structure
  - allow cure in bad weather
  - give a tenacious formulation
- Adjustments are made to recover maximum part strength
- Surface treatment of substrates significantly improves repair bond strength and durability.

5. REPAIR ASSESSMENT AND MEASUREMENT

When assessing and repairing any FRP structure there are many aspects that must be inspected and quantified. These are:

- To establish where physical damage exists
- Identify the type of damage, delamination, fracture, voids, disbonds, etc
- To identify when all the damaged area has been removed
- Locate presence of moisture
- Check satisfactory creation of an environmental envelope for repair to proceed
- Evidence of satisfactory cure cycle
- Evaluation of completed repair, including strength and bond line integrity

It is expected that every industry that undertakes repairs on FRP structures has its own rules, but any adoption of the high standards rigorously maintained within the high performance FRP repair sector will only benefit the quality and performance of repairs in less critical applications.

The areas of most concern in procedural measurement are:

- In preparatory work where moisture, dirt and surface contamination must be removed, cleanliness maintained and total laminate damage removed without creating further fibre damage

- Controlled drying under a maximum temperature limit that takes account of the saturated vapour pressure of the water. This limits temperatures to approximately 60°C for sandwich structures and 80°C for monolithic composites. Dirt and grease must be cleaned away with approved solvents. A clean, dry environment must be created and gloves worn preventing skin touch. When clearing identified damage, care must be taken not to destroy surrounding bond line joint areas when using power tools etc.

- Quality control of material selection in areas such as specified repair material's availability, quality and age has a significant bearing on finished repair quality

- Only OEM approved resins, reinforcement or prepregs should be used. If unavailable, local design approval should be gained prior to use. Certificates of Material Conformability should be obtained for traceability. ‘In House’ storage must be in accordance with the OEM recommended environmental envelope, chilled or frozen. Materials out of shelf life should be destroyed or catalysed and disposed of safely. In certain circumstances resins and adhesives can be re-graded for less critical use.

- Creation of ideal repair working conditions. If parts are too large or difficult and expensive to transfer to a workshop then a localised monitored ‘tent repair cell’ should be created

- Resins need to be processed within a known temperature and humidity envelope to achieve optimum performance. Inferior repair quality occurs when these parameters are breached, often resulting in premature breakdown of the repair, while processing times and repair costs are increased.

- Monitoring and eliminating foreign inclusions and voids. These can be caused by dirt under protective papers, release films or by trapped air. They are generally due to poor laminating techniques and if not eliminated can reduce the strength of final repair.

- Elimination of inclusions is achieved by procedural monitoring, as a laminate is built up. Voids are difficult to measure during repair but can be excluded using vacuum techniques and compaction prior to resin gelation. NDT measurement can record density of voids and OEM designers often quantify their permitted proximity to approve or reject the repair

- Final repair inspection. Prior to allowing a part to return to service the completed repair requires NDT and performance testing approval to pre-determined standards.

- Visual inspection and an expert check of the repair records are sufficient for some industries. If a critical repair has been carried out then NDT or sample destructive testing should be undertaken.

It is of paramount importance that long term records are maintained for all repairs undertaken and that records are updated at regular service inspections that assess life performance. Should failures recur, then statistical data would be available to categorise the quality of a particular repair technique or inspection method.

Practical detection of damage or flaws in a FRP structure, the control of process parameters and the assessment of a finished repair as ‘fit for purpose’ can be undertaken using a wide range of techniques with varying degrees of accuracy, dependent on particular requirements. Inspection or assessment equipment also ranges widely in cost, from visual methods and a manual coin tap or mechanised version of the same, through to sophisticated acousto-ultrasonic assessment, using neural network waveform and frequency spectra pattern recognition analyses (a laser shearography or strain mapping system). All have gained approvals for inspection of the same types of damage detection in the aerospace industry, and are referred to in Boeing, Airbus, Fokker and other authorised aircraft repair manuals.

The application of specific NDT/NDI methods varies between industry sectors, and it is apparent that reliance on any one particular inspection method for proving a part’s acceptance is fine for some companies whereas other FRP manufacturers would not even consider its use. Generally, existing standards bodies throughout the world publish details of recommended practices for the testing of FRP.

In practical terms any test must have easy to interpret accurate results and generated fairly rapidly. It is costly to have a piece of machinery or vehicle out of service, so effective NDI apparatus is an essential part of repair planning. Equipment should be portable, robust, safe to operate and affordable.

In addition to conventional mechanical testing, laboratory NDT equipment preferences include various types of radiography, ultrasonic C-scan, acoustic emission and, more recently, thermography, shearography, laser strain mapping and tomography.

Automatic tapping devices and hand held moisture meters are commonplace equipment. More sophisticated laboratory based NDI conversions are available for in-field operation. However, some of the techniques are limited by size, weight and the hazardous nature of the equipment required.

Those techniques preferred by the aerospace, marine and military industries for repair assessment include ultrasonics, acoustic emission, and more recently thermography, shearography and acousto-ultrasonics. However, until the major FRP manufacturers adopt new methods, such as shearography for production quality control, the majority of NDT engineers will remain loyal to well tried technologies for damage and repair assessment.

As time passes more reference standard data is generated, electronics hardware and computer software becomes more capable, so enabling dramatic advancements in all measurement techniques. Detection of flaws in composite structures will be more reliably located, and engineers, buyers and customers can operate with greater confidence [39-50].

Repair bond line strength is the one physical condition that is still difficult to assess and is thus a major concern to industry. Delaminations and disbonds can be identified by existing means such as mechanical impedance, ultrasonics or acoustic emission but these techniques report failure after the event has occurred. Although research is on-going to develop known and new NDT techniques to identify a solution, currently only mechanical destructive testing appears to be a reliable method to confirm the adhesive's strength and comparative bond line strength prior to peeling.

6. THE NEED FOR TRAINED PERSONNEL

It is essential that repair training is conducted to a consistent standard throughout the world and that companies are encouraged to be responsible when undertaking supplementary skills improvements. This scheme already exists in the servicing arms of both civil and military aerospace sectors. CACRC is able to offer guidance on suitable sources of training for high performance structural repairs either as a practical exercise or as background training to give operators an appreciation of the levels of quality expected. Over the years numerous documents have been published on the care required for joining materials, including the subjects of adhesive bonding of polymers, composites, preparation, cleaning, joint design, materials, and other related procedures.

Once a repair has been completed and certified, test evidence will confirm the degree of strength returned to the original part. The continued safety of the user or the product is the overriding factor when assessing the quality of the repair, so the pre-determination of safety factors through continuous condition monitoring and the performance testing of repairs are the only ways to provide guarantees. The ability to recognise defects and assess repair quality is a skill, which can only be gained through experience or professional inspection training in NDT and other relevant test equipment.

7. CONCLUSIONS

The more primary a structure is, and the closer it operates to its design limits, the more difficult the repair. However, even heavily-loaded primary structural FRPs have been successfully repaired for many years. Heavily loaded, oriented-fibre, advanced FRP structures require careful engineering design of major repairs; it is not simply a matter of applying a patch.

Given a good repair design, the competence of the repair technician becomes critical. Vacuum-bagging becomes virtually mandatory for advanced FRP repairs, in order to achieve the required compaction and proper consolidation of the repair plies.

Prepreg can sometimes be repaired with prepreg itself or wet materials in field conditions; autoclaves for repairs are rarely necessary.

FRP repairs can be quite time-consuming, and require careful attention to detail. Most of these repairs rely fundamentally on high-quality adhesive bonding. The strength of an adhesive bond cannot be measured without destroying it. Therefore, careful control of the repair process, especially regarding cleanliness, fit of the repair patch, and meticulous surface preparation of the bonding surfaces, becomes crucial. It all goes back to the skill, training, and integrity of the person doing the repair.

In spite of all these obstacles, successful repairs of complex FRP structures are being done every day. There is no “black art” to FRP repair; just training and experience. Experimentation will always prove best practice and clear-up uncertainties. Finally, quality assurance is an absolute must, requiring a thorough understanding and dedication to underlying principles and the testing required to ensure the repair will be successful long-term.

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ANNEX 1: SAE STANDARDS FOR REPAIR OF FRP STRUCTURES

SAE Aerospace recommended practice	***Date published***	***Document type***
ARP1333 : Non-destructive Testing of Electron Beam Welded Joints in Titanium Base Alloys	03/01/1974	Standard
ARP1611 : Quality Inspection Procedure, Composites, Tracer Fluoroscopy and Radiography	11/01/1995	Standard
ARP4118 : Isolation and Corrosion Protection of Dissimilar Materials	06/01/1994	Standard
ARP4916 : Masking and Cleaning of Epoxy and Polyester Matrix Thermosetting Composite Materials	03/01/1997	Standard
ARP4977 : Drying of Thermosetting Composite Materials	08/01/1996	Standard
ARP4991 : Core Restoration of Thermosetting Composite Components	12/01/1998	Standard
ARP5089 : Composite Repair NDT/NDI Handbook	11/01/1996	Standard
ARP5107 : Guidelines for Time-Limited-Dispatch (TLD) Analysis for Electronic Engine Control Systems	11/15/2006	Standard
ARP5143 : Vacuum Bagging of Thermosetting Composite Repairs	07/26/2002	Standard
ARP5144 : Heat Application for Thermosetting Resin Curing	03/01/2000	Standard
ARP5256 : Mixing Resins, Adhesives and Potting Compounds	03/01/1997	Standard
ARP5319 : Impregnation of Dry Fabric and Ply Lay-Up	07/19/2002	Standard
ARP5577 : Aircraft Lightning Direct Effects Certification	09/30/2002	Standard
ARP5605 : Solid Composite Laminate NDI Reference Standards	09/01/2001	Standard
ARP5606 : Composite Honeycomb NDI Reference Standards	09/01/2001	Standard
ARP5701 : Lay-up of Pre-preg Composite Materials	Work in Progress	Standard
J1032 : Definitions for Machine Availability (Off-Road Work Machines)	04/01/1987	Standard
J1344 : Marking of Plastic Parts	07/01/1997	Standard
J1555 : Recommended Practice for Optimizing Automobile Damageability	06/19/2000	Standard
J1573 : OEM Plastic Parts Repair	02/25/2003	Standard
J1781 : Ship Systems and Equipment - Materials for Fluid Systems	11/22/2006	Standard
J1828 : Uniform Reference and Dimensional Guidelines for Collision Repair	11/07/2006	Standard
J2376 : New-Vehicle Collision Repair Information	03/07/2005	Standard
Vehicle E/E Systems Diagnostic Standards Committee	08/01/2001	Standard
J2403 : Medium/Heavy-Duty E/E Systems Diagnosis Nomenclature	08/25/2004	Standard
J2667 : Strsw (Squeeze Type Resistance Sport Welding) Equipment Acceptance Criteria for the Collision Repair Industry	10/26/2004	Standard

SAE Aerospace Information report	***Date published***	***Document type***
AIR1664 : Aircraft Flexible Tanks General Design and Installation Recommendations	10/01/1996	Standard
AIR4069 : Sealing Integral Fuel Tanks	05/01/1998	Standard

AIR4844 : Composites and Metal Bonding Glossary	09/01/1999	Standard
AIR4938 : Composite and Bonded Structure Technician/Specialist: Training Document	09/01/1996	Standard
AIR5278 : Composite and Bonded Structure Engineers: Training Document	03/01/1999	Standard
AIR5279 : Composite and Bonded Structure Inspector: Training Document	03/01/1999	Standard
AIR5367 : Machining of Epoxy and Polyester Matrix Thermosetting Composite Structures	Work in Progress	Standard
AIR5416 : Maintenance Life Cycle Cost	Work in Progress	Standard
AIR5431 : Repair Tooling	12/29/2004	Standard
AIR5702 : Storage and Handling of Epoxy Thermosetting Composite Materials	Work in Progress	Standard
AIR5885 : Landing Gear Common Repairs	12/01/2004	Standard
AIR5946 : Design and Application of Composite Repairs for Thermosetting Composites	Work in Progress	Standard
AIR825/12 : Oxygen System Integration and Performance Precautions	03/25/2003	Standard

SAE Aerospace Material Specifications	***Date published***	***Document type***
AMS2694 : Repair Welding of Aerospace Castings	04/01/1984	Standard
AMS2950 : Paste Adhesive For Core Restoration	Work in Progress	Standard
AMS2950/1 : Paste Adhesive for Core Restoration-General Requirements and Qualification Program	Work in Progress	Standard
AMS2960 : Glass Fabric with Epoxy Resin Wet Lay Up Repair Material	Work in Progress	Standard
AMS2960/1 : Glass Fabric with Epoxy Resin Wet Lay Up Repair Material - Part 1	Work in Progress	Standard
AMS2960/5 : Glass Fabric with Epoxy Resin Wet Lay Up Repair Material - Part 5	Work in Progress	Standard
AMS2980 : Technical Specification: Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 0 - Introduction	01/26/2006	Standard
AMS2980/1 : Technical Specification: Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 1 - General Requirements	01/26/2006	Standard
AMS2980/2 : Technical Specification: Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 2 - Qualification Program	01/26/2006	Standard
AMS2980/3 : Technical Specification: Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Purchasing Specification - Fabric	01/26/2006	Standard
AMS2980/4 : Technical Specification: Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Purchasing Specification - Resin	01/26/2006	Standard
AMS2980/5 : Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 5 - Material Specification: Carbon Fiber Fabrics, Plain Weave, 193 G/MD2, and Epoxy	01/26/2006	Standard
AMS3970 : Carbon Fiber Fabric Repair Prepreg, 125Mdc (250Mdf) Vacuum Curing Part 0 - Introduction	12/01/1999	Standard
AMS3970/1 : Carbon Fiber Fabric Repair Prepreg, 125Mdc	12/01/1999	Standard

(250Mdf) Vacuum Curing Part 1 - General Requirements		
AMS3970/2 : Carbon Fiber Fabric Repair Prepreg, 125Mdc (250Mdf) Vacuum Curing Part 2 - Qualification Program for Fiber, Fabric, Resin and Film Adhesive	12/01/1999	Standard
AMS3970/3 : Carbon Fiber Fabric Repair Prepreg, 125Mdc (250Mdf) Vacuum Curing Part 3 - Purchasing Specification for Epoxy Prepreg	12/01/1999	Standard
AMS3970/4 : Carbon Fiber Fabric Repair Prepreg, 125Mdc (250Mdf) Vacuum Curing Part 4 - Purchasing Specification for Film Adhesive	12/01/1999	Standard
AMS4235 : Aluminium Alloy, Castings 4.6cu 0.35mn 0.25mg 0.22ti (A206.0-T71) Solution and Precipitation Heat Treated	01/01/1987	Standard
AMSDTL23053/15 : Insulation Sleeving, Electrical, Heat Shrinkable, Polyolefin, Heavy-Wall, Coated, Flexible, Outer Wall Crosslinked	07/01/1999	Standard
AMSS83318 : Sealing Compound, Polysulfide Type, Low Temperature Curing, Quick Repair, Integral Fuel Tanks and Fuel Cell Cavities	Work in Progress	Standard
AMSS8802 : Sealing Compound, Temperature Resistant, Integral Fuel Tanks and Fuel Cell Cavities, High Adhesion	03/03/2005	Standard

Other SAE Standards	***Date published***	***Document type***
AS176 : Limits, Table of Limits and Lubrication Charts	10/01/2001	Standard
AS7118 : Nadcap Requirements for Composites	05/26/2004	Standard
MA4872 : Paint Stripping of Commercial Aircraft - Evaluation of Materials and Process	03/01/1998	Standard

ANNEX 2: DAMAGE TERMINOLOGY

Abrasion: The wearing away of a portion of the surface by either natural (e.g. rain, wind), mechanical (e.g. misfit), or man-made (e.g. over sanding) means; penetrates only the surface. In a FRP, does not damage the first ply.

Burned: Showing evidence of thermal decomposition or charring, through some discolouration, distortion, destruction, or conversion of the surface of the plastic, sometimes to a carbonaceous char.

Charring: The heating of a FRP in air to reduce the polymer matrix to ash, allowing the fibre content to be determined by weight. A similar effect in service caused by lightening strike, fire or other source of overheating.

Chemical attack: Damage to the resin matrix by accidental contact with or unauthorised us of chemicals.

Crack: Fractures in either matrix or both matrix and fibres. An actual separation of material. Does not necessarily extend through the thickness of the FRP, but can be stopped by differently oriented plies.

Delamination: Separation of the layers of material in a laminate, either local or covering a wide area. Can occur in the sure or subsequent life of a part.

Disbond: An area within a bonded interface between two adherents in which an adhesion failure or separation has occurred. It may occur at any time in the life of the structure and may arise from a variety of causes. Also, colloquially, an area of separation between two laminate in the finished laminate. (in this case the term delamination is normally used).

Erosion: Destruction of metal or other material by the abrasive action of liquid or gas. Usually accelerated by the presence of solid particles of matter in suspension and sometimes by corrosion. In the case of aircraft, it can also be accelerated by hail, heavy rain, dust, and especially the occasional sandstorm or volcanic ash blown to high altitude.

Fracture: The separation of a body. Defined both as rupture of the surface without complete separation of laminate and as complete separation of a body because of external or internal forces (i.e. some layers are broken or the whole part is completely broken).

Impact: Damage from a foreign object (other than ballistic). Usually a dropped tool or collision with a vehicle or structure. In flight it may be caused by hail impact or bird strike.

Scoring: a type of wear in which the working force acquires grooves, axial or circumferential, according to whether the motion is reciprocating or rotary. Also applied to a similar effect on the rigid or non-moving member. A groove that is smooth and has significant width compared to depth. A blunt scratch.

Scratch: An elongated surface discontinually, which is extremely small in width compared to length. Shallow mark, groove, furrow, or channel normally caused by improper handling or storage.