Repair and Inspection of Composites:
Review Report

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PERA

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PREFACE

Composite 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 composite structure is damaged or when an unsatisfactory repair is completed, some evident on the surface, but most hidden.

The overall objectives of this document 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 an extensive world-wide technical literature review undertaken using existing published works, procedures, databases, the internet, and through direct industrial liaison. It presents an overview of composites repair and inspection techniques that exist throughout most sectors of industry, how the skills are implemented, how repair quality is maintained and what new developments are on the horizon.

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 composites.

A detailed search of public domain literature, conference reports, standards, manufacturing procedures and promotional material was undertaken to establish those composite repair and measurement techniques that have gained acceptance or been documented. This work, through industrial liaison, the world-wide web, technical journal review and CD-ROM based databases has identified techniques for the repair of all varieties of composite constructions in a wide range of materials.

1 INTRODUCTION

The growth in the use and application of fibre reinforced composites 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 a product is conceived, materials are selected that will satisfy specified performance requirements and can be incorporated into a functional structure or assembly. The shape will usually 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 [App3 102-105].

The option should then exist to repair or replace. If it is low cost then direct replacement does not become a problem, this being the case in many cosmetic non-structural uses of fibre composites. However, repair procedures have been developed because replacement parts are usually very expensive, and repair must be an option to make a product viable in a service situation. A recent estimate of cost of an unserviceable wide-bodied aircraft grounded on the runway is around £4000 per hour, so a composite repair programme is an essential part of this industry's maintenance support. Industry as a whole is aware that most metal structures can be welded, bonded, bolted, riveted etc., so expectations exist for composites to be satisfactorily repaired in a similar manner.

Widely varying levels of expertise are known to exist between different industrial sectors. Quantifiable certified repairs are regularly carried out on aircraft and marine vessels whilst in other industries repaired composite parts are either not acceptable or people are just not aware that structural repairs can be effected satisfactorily. Those supplying the automotive, process and leisure fields are the main sectors identified as needing guidance. Their reasoning is often blinkered purely on aesthetic grounds, as they believe the repair will be visible and unsightly, when in fact this can often be very far removed from the truth. This misconception can only be overcome by re-establishing the confidence in customers and product manufacturers alike by education and demonstration of the high quality of repairs that can be achieved. Once this has started to happen and industry centres of repair excellence have been established, along similar lines to UKAS test houses.

Damage can occur in many ways. If a part has been over stressed, then for safety reasons, it should be replaced as a matter of course whether it be made from metal, plastic, ceramic or any other material. The different levels of damage would be categorised to assess the complexity of repair that needs to be effected. Once a repair has been installed and certified, evidence will confirm to structural designers the degree of strength returned to the original part. This will demonstrate the prime cause of failures is often accidental damage that cannot be foreseen at the design stage [App2 17]. When this occurs it is essential that a full structural repair with cosmetic finishing can be effected to that product or the constituent materials, the different levels of damage being categorised to assess the complexity of repair that needs to be effected. Once a repair has been installed and certified, evidence will confirm to structural designers the degree of strength returned to the original part, to demonstrate how effective a repair can be and encourage the original buyer that this material is viable for use in other products in the future.

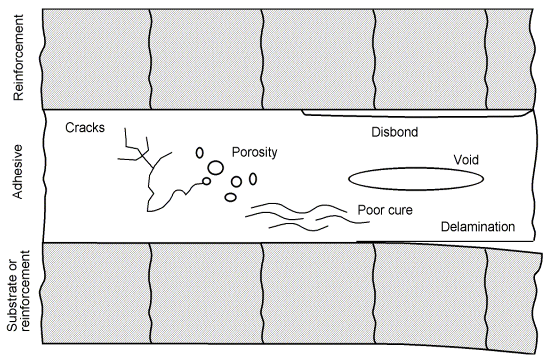

Figure 1: Laminate Adhesive Interface Defects

The aircraft industry demands high levels of safety for passenger, crew, and aircraft protection, and has built up an experience based database that has given them confidence to certify repaired composite parts. Planes have evolved from canvas stretched over wooden composites, to lightweight aluminium alloys riveted or bonded together, which are now being increasingly replaced by fibre composite skins and sandwich structures bonded in a similar manner. On modern aircraft over 40% of secondary structures and panels are produced from carbon, aramid, and glass fibre laminates, and constant repair facilities need to be available to keep aircraft in the sky.

Experience has shown that safety proven structural repairs can be undertaken cost effectively. Damage can be the result of lightening strike, hailstorms, bird strike, ground vehicle impacts, deterioration through moisture or hydraulic fluid ingress, or as is often the case, dropped spanners during regular maintenance. Once reported, repairs are undertaken only by OEM certified companies employing qualified technicians using strictly controlled re-manufacturing procedures and approved materials. These skilled personnel can effect high quality cost effective repairs to all manner of structural and airflow critical parts, and it is their level of competence and the close attention to mandatory procedures that needs to be re-created within the workforce of other industries through specialist training App2 10,3,15 App3 2,9,10,17,24,41,66,84,92,116,119,120.

To make this happen requires the re-education of industry through the dissemination of the results of this project to UK firms in general and the implementation of structured staff training programmes to build expertise in all types of composite repair. NVQ type training could be implemented through certified teaching organisations so that standardised levels of repair skills can be demonstrated for both design-critical repairs of structural areas and for those of simple cosmetic damage. These qualified people would be then become responsible for undertaking fibre composite repairs and/or assessing the repair quality, in a similar way to those welding engineers qualified to repair metal tanks to the ASME codes of practice for pressure vessels.

It is essential that repair training is implemented at a consistent standard throughout the world, and that companies are encouraged to be responsible when undertaking supplementary skills improvements. This scheme already exists within the servicing arms of both civil and military aerospace sectors. The CACRC are 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 elated procedures. This project will review many of these existing repair procedures from the many industries already using composites or manufacturing the raw materials and present new users with a range of graded technical procedures suited to full rectification of the different levels of component damage that can occur.

Currently, for safety reasons alone, it is generally considered that an aircraft's primary structures cannot be repaired, unless the necessary tooling and autoclave facilities are available. As more knowledge is gained in materials, design, condition monitoring, modelling and construction, confidence levels will rise and this final hurdle will no longer exist.

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 to potential composite users. The ability to recognise defects and assess repair quality is a skill, which can only be gained through experience or professional inspection training in NDI and other relevant test equipment.

In the USA, research is currently underway assessing the differing quality of repairs carried out by people trained to various levels of skill. Standard test pieces were repaired, NDI checked, and tested to failure by Wichita State University to study the effect of training on repair performance. Earlier statistical evidence generated by Boeing has shown that the best quality repairs are achieved by those trained members of their workforce that carry out the repair tasks methodically, and with most care and attention to detail. A good repair with minimal defects cannot be hurried.

2 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 that particular industry sectors needs.

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 grade materials. They currently 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 finished repair or destructive testing of sample coupons or bars. Ideally 'bondline adhesion strength' should also be measured, but it is apparent that at present no stand alone non-destructive method exists [App2 16,18]. Evolving research around the globe indicates that a solution is not far away.

Each industry sector has set its own standards for quality control within repair procedures, structural repairs of aircraft being the most exact. 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 composite materials and should also be consulted when designing repairs in jointed structures [App3 26]. 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 repeatedly not realised how difficult composites 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 composite prior to bonding, whilst thermoplastic composites 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 composites by most surface treatment methods [App3 122,123]. Established surface activation techniques, corona discharge, flame treatment [App3 31], 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 fibrous 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.

2.1 General Repair Guidelines

As detailed earlier, 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 the creation of the optimum envelope for production of the best repair.

When damage occurs to structures, whether they are chemical vessels, bridges, buildings, ships, motor vehicles, or aircraft out in the field, it never happens in the ideal location where repair facilities are readily available. A decision needs to be made whether the repair can be carried out in-situ due to position, size or complexity of 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 must be repaired. It is the additional costs that surround a repair situation that affects how a repair should be undertaken. As mentioned earlier when a scheduled civil passenger aircraft is forced out of service due to an unacceptable damage report, it's grounded costs are exorbitant whilst it is awaiting urgent maintenance, as it is only earning money when it is in the sky. 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. Whereas, for the automotive sector involving a lower cost item 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 deemed imperative that a repair is effected immediately to prevent further damage occurring, 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 created around the damaged area, isolating it from the prevailing weather conditions. Using sheeting and adhesive tapes to form a tent, and temperature control.

- The area created should be made free of dust, soot, and 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 dilutents etc. during repair procedures then provision must be made to safely remove these without causing risk to operator or prepared environment, i.e. extraction airflow can chill heated areas.
- Basic services i.e. compressed air, electricity, water, and vacuum must be made available for standard repair and test equipment to function.

A typical repair procedure uses the following key steps:

- Establish the extent of the damage and assess whether part is repairable
  - Visual techniques for external
  - NDT techniques for internal
  - Rebuild if too damaged
- Establish type of damage: - moisture ingress, disbond, delamination, etc.
- Cut out and remove all damaged material until only sound laminate remains (If surface has protective coating i.e. paint this must cut back to create a land 20mm from edge of 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 repair technique to be effected
- Thoroughly clean, degrease, and ideally carry out ‘water break test’ (Appendix 1)
- Thoroughly dry the damaged laminate and prepared areas
- Select materials for repair: All fresh, within shelf life and at working temperatures
- Weigh out resin proportions to ensure correct fibre volumes for retention of structural properties, if using ‘wet lay’
- Cut reinforcement patches to sizes needed (exact or overlap) and orientation
- Prepare laminating and curing equipment
- Carry out repair to ‘best practice’ ensuring no processing defects occur
- Monitor cure cycle and environmental envelope to enable certification of repair
- Inspect finished repair and certify

2.2 Composite Repair Styles

2.2.1 Patch

The most common repair carried out on all types of composite is the patch repair. It is a simple low cost repair that needs the least preparation, is functional and fast to carry out, ideal for urgent ‘field repair’, but ban 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 [App3 22]. It is also possible to use the patch to improve the strength of existing undamaged structures, enabling them to support higher loadings [App3 67-69], or to easily overcome identified design weaknesses in a structure.

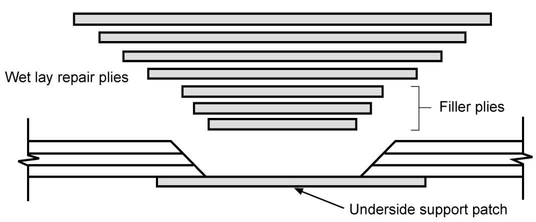

Figure 2: Laminated Patch Repair

2.2.2 Scarf Joint Repair

A joint style 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.

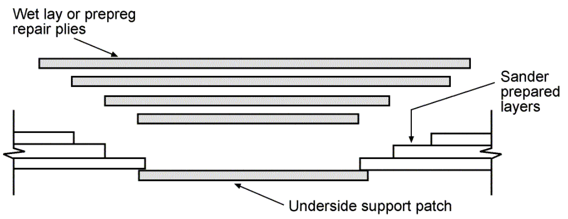

Figure 3a: Stepped Scarf Repair

This type of joint can reliably restore 90% of the original strength of the undamaged material, and is specified in most aircraft repair manuals [App2 13,16]. 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.

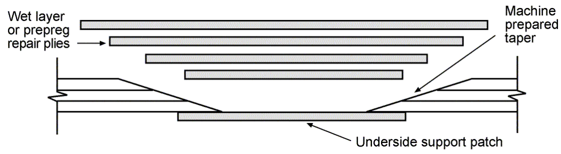

Figure 3b: Tapered Scarf Repair

Repair procedures are usually designed to achieve a scarf shear strength approximating to twice the tensile strength of the present material [App3 120]. Fibre damage to remaining material around the scarf during abrading must be minimised to ensure further weakening of the

DEFECTS	REPAIR TYPES				
	Glass Fibre Laminate			Carbon Fibre Laminate	
	Vinyl Ester Scrimp	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
Aireation	Resin Infusion or Scarf	Patch, Plug or Scarf	Patch, Doubler or Scarf	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 1: Typical Defects and Repair Approach

laminate's construction does not occur, so operator skill is high and the attention to detail required make this style 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.

2.2.3 Pre-Cured Doubler

This repair technique has been developed by the aerospace industry as an attempt to minimise the out of service delays that keep planes out of the sky [App3 90,94].

The doubler, Figure 4, is a pre-cured 'plaster' that has been designed and manufactured by mass production in a controlled composite manufacturing facility. It would have 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. It would appear to have achieved what it set out to do, and is gaining enthusiastic support from industry.

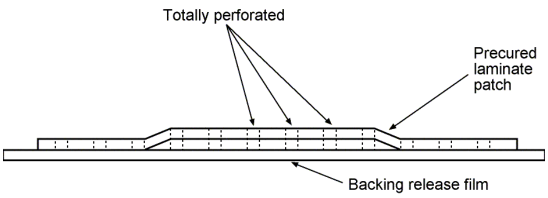

Figure 4 - Adhesive Bonded Doubler

2.2.4 Plug

The original repair to any puncture situation, which historically would be effected to a holed ship with wood, wadding and pitch.

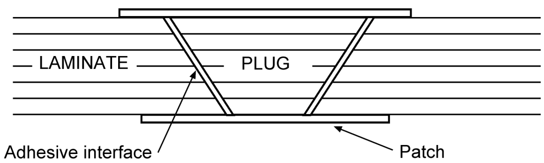

Figure 5 - Adhesive Bonded Plug Repair

The application of the technique to modern day composites 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.

2.2.5 Bolted Plates

An alternative to the plug or patch repair, bolted repairs are still commonplace in aircraft and marine industries and much research has taken place into their use with composite 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 people to prevent further damage due to drill wander or inner surface breakaway and to ensure inner surface breakaway and to ensure inner surfaces such as fuel cells are not penetrated.

2.2.6 Resin Infusion or Injection Repair

A repair technique developed to restore the original part to near design compressive and shear strength by the injection of low viscosity structural adhesive into a delaminated structure, with the use of vacuum to re-bond the ply surfaces together, consolidating the structure until resin cure has been completed. Used in both aircraft repair [App3 24] and marine applications as a production (SCRIMP) [App3 63] and repair system (RIFT).

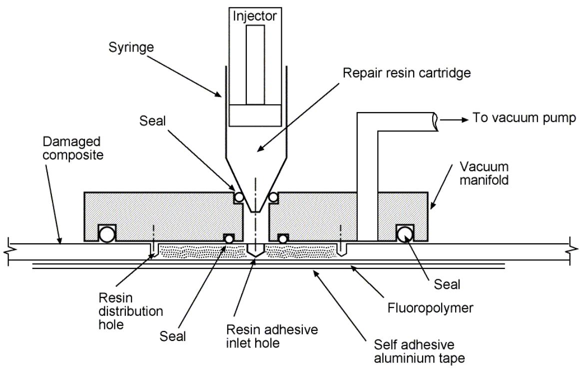

Figure 6 - Resin Infusion or Injection Repair

It is a fast inexpensive repair that eliminated the need for careful surface preparation, and can be undertaken in-situ. Is a popular field repair 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.

2.3 Industry-Specific Repair Techniques

Following consultation with industry and world-wide published technical information sources, the following procedural trends for composite repair have been identified within the different industry sectors. 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 CSM

- Chemical
  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

2.3.1 Automotive Industry

Generally the repairs effected to motor cars, trucks, and other vehicles constructed from fibre composite materials are of a cosmetic rather than structural nature. The use of composites by automotive OEM's tends to be for body panels, roofs and floors hanging on rather than as structural parts. Often due to time restrictions and cost, parts are replaced rather than repaired. Currently major composite vehicle producers such as TVR or Lotus have confirmed that they generally cut away major damage and replace with new sections.

When more repairs are carried out, it is to manufacturers guidelines only, by non- or semi-skilled personnel who create repairs that are basically weatherproof or aesthetically pleasing [App3 22,23,70]. Where structural parts are damaged then these 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, 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.

2.3.2 Chemical Industry

The chemical industry utilises composites in the manufacture of pipes, valves, pressure vessels, and tanks. Composites 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, installation and the design freedom available with 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 or fractured during installation or service by impact or earth movement they would either be replaced or patch repaired depending on the critical nature 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' highlights the attention to detail necessitated 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 application this could be on a continual basis, until a replacement part was installed or an in-situ over laminated repair effected [App2 1,9,13,19,20].

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

2.3.3 Construction Industry

Polymer composites 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 the climatic changes and geological movements within our planet. FR is now at the forefront 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 the support or repair of damaged concrete and steel composite structures.

Bridge supports, piers, motorway sections etc. that have become weakened due to forceful external damage or weathering / internal corrosion can be satisfactorily reinforced. This is achieved either by the external structural adhesive bonding of pultruded carbon fibre composite 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 [App3 27,68].

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 the sealing of defects caused by water ingress into the structure of pre-cast sectional buildings.

Composite repair and stiffening materials have successfully been replacing steel-based reinforcing systems despite the considerable cost differences between metal and composites. Applications that have utilised the 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 seen to be growing rapidly as more towns in earthquake regions endeavour to protect existing buildings from the devastating effects of these shock waves. Although much of the application activity would appear to stem from America and Japan who have these suspect zones in their countries, Europe's buildings and bridges are gaining the benefit of composite structural repair systems.

The information provided has shown that many repairs need to be carried out satisfactorily in the extremes of known climatic conditions, so preparation of bondline joints can be critical to achieve maximum adhesion. The substrate surface needs to be blast cleaned to remove dirt, loose material, and create a key for adhesion promotion. Although it would be ideal to have low moisture levels and operate in warm ambient temperatures this is rarely possible, so adhesive chemistry has been adapted to be useably in a wider environmental envelope and using localised moisture, up to 5% maximum to assist the resin curing mechanism. To help repair contractors in the USA, resin makers such as Morton Thiokol developed epoxy resins for pre-impregnated fibre mat applications that have long shelf lives of up to a year without the need for special temperature controlled material storage equipment.

Typical Repair Design used: External Patch

2.3.4 Marine Industry

Encompassing the leisure craft, commercial and military surface vessel sectors, there has been a gradual change over the last forty years to the use of polymer composites as a direct replacement for timber and metals. As a result of the diverse specification improvements available from composite 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 adverse weather conditions.

There are many similarities with the type of damage that occurs in GRP craft and other marine structures to other composites – skin puncture, moisture ingress, delamination, fibre crushing, and blistering are all common. Situations can also be aggravated by constant contact with the seawater environment, often resulting in osmotic blistering which then needs specialist rectification. Also 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 to that utilised in the aerospace industry where sophisticated design technology, automated fibre placing, autoclave cured prepreg laminates and 100% NDI of components are typical. So, 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 used are generally similar to other industries, with the one chosen being dependent on the structural nature and aerodynamic 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 could be a prepared scarf joint with over-lamination on inner the face and a second smaller scarf cut on the outside of the repair to allow for a build up of gelcoat on the outside of the repair material. These types of repair have been carried out on racing yachts, pleasure craft, military vessels and lifeboats to enable them to remain in service [App3 36]. Usually access from both sides is possible with a boat so the scarf can be cut on the inside of the hull. Typical scarf slopes seem to be between 40-100:1, and there is usually a small 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 that is gaining acceptance for delaminated structures is that of 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 used also in the strengthening and repair of steel infrastructures in civil, offshore and defence industries App3 24.

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

2.3.5 Aerospace Industry

Three main sectors are covered in this category Military, Civil Aviation, and leisure driven Light 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 composite materials in jet aircraft and helicopters stems from many years' development. The wealth of design and performance data generated from the usage of different materials and constructions has provided the industry with historical references for the establishment of proven design and repair safety factors. 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, controlled by independent organisations (CAA etc.), that should ensure a sound quality repair of known performance is undertaken. The technologies, materials, and equipment that have evolved for damage detection, safe controlled repairing and inspection of aircraft structures are reliant on close attention to procedural detail. Aircraft designers and manufacturing companies specify:

- Which parts of a composite structure can be repaired
- How large a damaged area or how many individual pieces of damage can be permitted in an area 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 lightening strike, using a range of approved repair methods and the appropriate materials.

These repairs would be 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 volumes to be achieved. Following a temperature regulated resin cure, generally under vacuum, the resultant completed repair should satisfy the design specification of the original laminated part on satisfactory inspection using non-destructive methods.

Every application is treated differently, but generally all repair procedures will follow aircraft OEM published recommendations that are written to achieve a full strength structural repair, and minimise operator error.

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

3 MATERIALS

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

As the range and properties of composite materials is vast, and their storage and supply can be a logistical nightmare, 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 more recently polyurethane chemistry, which offer excellent bond strengths coupled with toughness that 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. Figure 1, earlier, shows the types of defects that occur, and the causes for them are described below.

- Cracks: due to high exotherm during cure, resin rich areas, 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 moister, poor mixing, incorrect cure.
- Poor Cure: bad mixing, poor temperature control, wrong environmental envelope (which reduces the binding properties (cohesion) within the adhesive resin).

A more detailed breakdown of these resins and associated fibrous reinforcement is shown in the following sections.

3.1 Resins for Repair

Resin systems move forward with new developments and advances in evolving chemistry. Although many systems can be repaired with similar chemistry, improvements in the performance of individual resins will often have occurred and, where QC 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 are frowned upon by many industries, aerospace especially. However guidance committees such as the CACRC set up by groups of concerned authorities within this industry are currently attempting to direct the original equipment manufacturers to approve generic material types and related quality / performance specifications, rather than to approve only individual manufacturers' products in composite part development.

To ensure a compatible material is used for repair is of prime importance. 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 would meet the performance criteria and service conditions of the product.

Composite repairs are generally carried out using wet resin lay-up with dry fibre reinforcement, adhesive bonding of pre-cured composite 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 lapsed.

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, to ensure minimum stockholding by users always carries premium charges.

The resin systems listed below are some of the preferred ones that have been located whilst reviewing different industry practices. 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.

3.1.1 Epoxy Resin

Extensively used in advanced structural composites, complementing polyesters as the most commonly used high performance resins. There is a wide choice of grades providing variations 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.

Commonly used resins are:

- Ciba Geigy LY/HY5052 - MoD approved for GRP structural repairs to minesweeper vessels
- Ciba Geigy UW43 HV pt A&B - MoD approved for GRP underwater repairs to minesweeper vessels
- Ciba Geigy Araldite MY 753 - MoD approved for repair to minor GRP items
- Sikadur 30 Polyamine based, Highways approved, low water absorbing adhesive paste for CFRP bonding (Compressive strength >100N/mm^2, E-modulus 12800N/mm^2)
- Hysol EA9396 - British Aerospace approved adhesive for CFRP patch/ doubler
- Other aerospace approved epoxies:
- Hysol EA9390 - approved by Boeing,
- Hysol EA9394 - paste adhesive to bond core materials to themselves and skins
- Hysol EA9628 - film adhesive repair plies to skin or honeycomb,
- Boeing BMS -5-129
- Ciba Epocast 52 (currently being evaluated for approval to SAE AMS 2890),
- Fiber Resin Corporation EY3804,
- Ciba Geigy LY 5052/HY5052,
- Ciba Araldite 501 - approved by ATR, is very brittle material but wets out fabrics well,
- Shell Epikote 815+RTU (now Ancamine 1483) or Epikote 816+RTU, are both old but good well proven materials.

3.1.2 Polyester Resin

The most widely used thermosetting resin for composite manufacture, due to its low cost and ease of processing. Popular for general commercial applications, including leisure products, tanks, sanitary-ware, and automotive accessories.

Common resins are:

- Scott Bader Crystic Isophthalic 625TV MoD approved used on some small craft
- Scott Bader Crystic 489 & 489PA MoD approved used on SRMH 5 onwards
- Scott Bader Crystic 189LV Naval approved resin for repair of small items
- BIP Beetle 838 MoD approved for small craft
- DSM Synolite 73-2787-T-1 alternative MoD approved repair material
- Crestomer 1200 toughened resin

3.1.3 Vinyl Ester Resin

Chemically very similar to polyester resins but with enhanced chemical and temperature resistance properties. Less expensive than epoxy resins. Used in automotive vehicle and marine vessel manufacture where higher service temperatures are expected, and in repair of Vinylester and polyester GRP as a laminating or injection resin. For the filling of internal voids, repairing disbonded cores, bonding internal delaminations, to provide a high performance repair.

- Dow Derakane 411-45 not pre-accelerated MoD approved for hand lamination and repair alternative to polyester.
- Dow Derakane 411-C50 low viscosity injection system resin MoD approved for SCRIMP fabrication/ resin infusion.

3.2 Fibre Reinforcements

The main types of material used in structural composites 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 composite laminates. The advantage of using the reinforcement in this form is that it enables the creation of a well defined laminate, as the individual fibres are pre-secured in their intended orientation prior to consolidation in a resin matrix. Fabrics may be 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

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 low duty 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 though the easiest material to effect an emergency patch type 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, the plain ones have simple weave patterns 'over one under one' which introduces quite large gaps between the 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 composite laminates are multi-contoured in shape, it is essential that the fabric used has the ability to drape in order to obtain the best mechanical properties and this feature is obtained by varying the weave pattern. Alternatives include 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 another alternative, 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/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 manufacturer's materials specifications. The SAE AIR 4844A Composite and Metal Bonding Glossary is recommended for reference when looking at fibres and fabrics in more detail.

Listed below are a selection of approved repair reinforcement materials used in ship and boat building, light/civil/military aircraft and other composite product constructions.

3.2.1 Glass Fibre

Woven Roving

- Fleming/Vetrotex WR780 - 780g/m2 MoD approved to NES 752
- Marglass 266 - 800g/m2, 5:4 bias weave
- Fothergill Y0530 - 780gm/m2
- Chomerat 780T - 780gm/m2, substitute for Y0530
- Ahlstrom R24/780 - 780gm/m2, alternative approved cloth
- Boeing BMS-8-79, surface protection fabric

Unidirectional

- Fothergill PW1347 - 620g/m2 MoD approved NES 752
- Fleming/Vetrotex UDC600/100 - 620g/m2 substitute for PW1347
- Chomerat UD600 - 600gm/m2 substitute for PW1347 with fixed weft
- Ahlstrom R24-620L - 620gm/m2 substitute for PW1347
- Carr DW0159 - 620gm/m2 substitute for PW1347

CSM

- Vetrotex M123 - 600g/m2 MoD approved powder based CSM
- (equivalents: Ahlstrom M510, OCF MK22, MK12 or Supermat)

All above approved for structural repairs using wet-lay methods. For infusion methods two, 4-harness satins also have MoD (NES 752) approval:

- Chomerat 800/S4 - 780gm/m2 or
- Carr GWR 770T - 780gm/m2 alternative cloth

3.2.2 Carbon Fibre

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

- Fabric style 3K-70-PW, to Boeing BMS-8-168
- Fabric style 3K-70-P, to BMS-9-8 type 1 class 2
- Fabric style 3K-135-8H, to BMS-9-8 type 1 class 2
- Fibredux M20/40%/G904 prepreg

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 British Aerospace, Airbus Division, Bristol.

3.2.3 Aramid Fibre

It is generally considered that due to the adhesion difficulties encountered with aramid, the recommended repair procedure would utilise glass fibre layers over any damaged areas.

Approved materials from aerospace use (Boeing) are shown in Table 2 below.

3.3 Summary

In general repair materials are similar to original, and can be 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
- Concrete Composite repaired by bonding Epoxy/Polyurethane with glass or carbon fibre mat
- Metal Composites repaired by thermoset adhesive bonding Epoxy/Polyurethane, or mechanical fastening or welding
- Surface treatment of substrates significantly improves repair bond strength and durability

Original Aramid	Glass Fibre Repair Material
BMS 8-218, style 120 BMS 8-219, style 120	Preferred: BMS 9-3, type D all classes except 1 and 15; or BMS 9-3, type H2 or H3 all classes except 1 and 15, but use only one ply in place of type D.
BMS 8-218, style 285 BMS 8-219, style 285	Preferred: BMS 9-3, type H-2 or H-3 all classes except 1 and 15; or BMS 9-3, type D all classes except 1 and 15, but use 3 plies of type D in place of one ply of type H-2 or H-3.

Table 2: Repair Materials for Aramid Laminates

4 REPAIR MEASUREMENT

Within the assessment and repair of any composite structure there are many aspects that must be inspected and quantified. These are:

- To establish where physical damage exists
- Identify 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 bondline integrity

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

The areas of most concern within procedural measurement are:

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

  Requires controlled drying within maximum temperature ceiling 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 greases 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 bondline joint areas when using powertools etc.

- Quality Control of material selection - specified repair material's availability, quality and age have a profound 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 to be in accordance with 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/adhesives can be re-graded for less critical use.

- Creation of ideal repair working conditions - if parts are too large or too difficult/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/humidity envelope to achieve optimum performance. Inferior repair quality occurs when these parameters are breached, often resulting in short life breakdown of the repair, while processing times and repair costs are increased.

- Monitoring and eliminating foreign inclusions and voids - generally protective papers, release films or trapped air, these can be caused by poor laminating techniques and if retained reduce strength of final repair.

  Elimination of inclusions should be achievable 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 documented can be sufficient for some industries. If a critical repair has been carried out then dependent on industry requirement or company preference NDT or sample destructive testing should be undertaken.

It is of paramount importance that long term records are maintained for all repairs undertaken, and records 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.

Details of industry preferred quality control methods can be found within the individual procedural manuals shown in Appendix 2 and within similar examples produced by major aircraft makers Boeing, BAe Airbus etc. or composite part manufacturers from other industries.

Practical detection of damage flaws within a composite, the control of process parameters and the assessment of a finished repair as 'fit for purpose' can be undertaken by a wide selection of techniques with varying degrees of accuracy, dependent on customer requirements. Inspection or assessment equipment can also range 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 parts acceptance is fine for some companies whereas other composite manufacturers would not even consider its use. Generally, existing standards bodies throughout the world currently publish details of recommended practices for the testing of composites.

Research undertaken through most industry sectors has highlighted the following existing and evolving composite inspection techniques and process control equipment applicable to their 'small batch' or 'one off' damage repair requirements.

4.1 Visual

The common sense approach used by all industries investigating evidence and extent of damage to any composite part, once it has been reported, is to initially look for surface defects. The use of normal eyesight is often sufficient to indicate where an impact or delamination beneath the surface has occurred. Line of sight can detect new undulations, indents or blisters on most surfaces, and with the aid of a concentrated light source shined at an acute angle over the surface, from something like a simple torch, any slight defect present would be identified by the casting of a shadow. Alternatively a specific piece of equipment can be used, called Difracto Sight, that benefits precisely from this technique.

If no damage is visible then NDI technologies should be used to ensure there is no hidden damage. Some structures have sufficient design strength to enable parts to continue in service with a known, but logged, number of defects. However, the majority require internal defects to be assessed for their extent, ability to be repaired, and likely cost of repair against replacement.

4.2 Coin Tap

The next approach to detection is the use a coin or other implement to manually tap the surface and listen for any changes in the audible emissions. This method can be a fairly reliable way of damage detection at negligible cost, it is widely used, aerospace industry approved, and available to everyone. The surface of parts can be mapped out and marked where the boundary of any audible change occurs. This is an easy-to-apply method that enables maintenance staff to quickly establish when delamination is occurring, and report that further investigation or a repair is necessary. However there are some reported reliability problems as no two people can always arrive at the same defect pattern, and the underlying structure has to be known within the search area. Sound difference only explains water ingress within a delamination. Changes in timbre can vary dramatically between structures, i.e. crisper high notes denote near surface [App3 33].

The test is carried out by tapping gently a few times at intervals of about 6mm to relatively quickly map out the damaged area. The sound difference is that a damaged area will emit a lower dull note, whilst that from a good bonded laminate will sound much higher and clearer. Once a pattern has been drawn on a non-structural laminate's surface, the damage should be cut out to that shape plus 12.5mm to provide a safety margin. For more critical parts it would be recommended to carry out further NDI assessment to confirm all damage has been removed before starting a repair.

The 'coin tap' technique is recognised in most aircraft repair procedural manuals as an alternative to high cost NDI methods. It works best on thin skinned sandwich structures where disbonds from honeycomb cores are easily identified. However, on solid laminates imperfections need to occur in the upper layers as it deep accurate detection is difficult [App2 16].

To improve control accuracy, aid striker repeatability and automate the technique a few manufacturers have developed electric tappers, equipped with facilities to provide permanent records of standardised map grids. More recent advancements in this field, using acousto-ultrasonic means, analyses the transfer functions waveforms and frequency spectra between in known transient pulse emitters and receiving AE sensors, and quantifies the type/extent of the damage between the pulse and receive transducers.

4.3 X-Ray Techniques

Radiography is a well-established technique normally associated with the detection of metal objects within x-ray transparent materials. X-rays pass through the component under test and impinge on a suitable detector, whether a film or an image intensifier. The presence of flaws, voids, and inclusions affects the absorption of the radiation, which causes a degree of shadowing on the viewed image. It has been used extensively in the aerospace and marine industries for in-line production inspection for helicopter rotor blades at Westlands and damage assessment/repair in road, floor and bridge strengthening by UK construction industry contractors [App3 33,49,51,53,83,130].

The technique is more suited to the detection of larger flaws, honeycomb core damage, water ingress and foreign inclusions in glass, aramid, or boron, fibre composites as the absorption characteristics of both carbon fibre and resin matrix is very similar and the overall absorption is low. Delamination flaw detection is also poor due to the very small changes in overall radiation absorption. Penetrants can be used to enhance the results, but are not recommended if subsequent repair is necessary as the substance will contaminate the material.

X-ray NDT should really be considered as complimentary to other flaw detection methods, which may offer improved detection capability in other planes.

Personal protective equipment must be provided for operator safety. Where portable equipment is used, it is often less sensitive, can be cumbersome and radiation emissions must be protected against by evacuating the surrounding area. This subsequently imposes repair cost penalties due to delays created on adjacent work.

Much research is ongoing to improve the effectiveness of radiation examination of composite parts, one being computer tomography (CT or CAT scanning) [App3 19,59-61,68,84]. Having evolved from advances in medical inspection and NDI of military components, this radiological digital scanning technique utilises the rapid improvements available in computer processing power to create real time x-ray images. The CT image is a 2-D slice through a 3-D image, and enables composite damage, defects, and foreign inclusions to be positioned more accurately. The massive cost of CT equipment however denies the use of this technology to general repair service companies, and only the major aircraft builders and materials research organisations are likely to have the constant demand to justify such capital investment.

4.4 Acoustic Emission

Acoustic Emission is an established NDI tool used extensively in both development and production testing of composite structures. Under test conditions the acoustic emission from any product is the audible sound generated as induced stresses instigate delamination, fibre breakage, matrix cracking, fibre matrix debonding and fibre pull out. Crack type events are usually very sudden, discrete, snap-like step functions, and tearing is usually a seemingly endless cascade of such events. AE can be classed as a non-destructive test due to the precise control of the operating systems. The application of an appropriate stress causes acoustic emission, indicating that micro failure is occurring and at the same instant allowing the applied load to be terminated before significant damage occurs. These changes in stress wave emissions, at the split second point of creation, are sensed at distances up to 0.5 metres independent of orientation or depth, by piezo-electric detectors coupled to the material. Dependent upon the nature of the material and the damage, the onset of emission occurs at between 5-70% of ultimate strength for most composites. The ‘rule of thumb’ where little experience exists for a particular component is to use 50%. This early detection increases the sensitivity of load testing considerably, and for composite tanks allows the test stress level (as defined in the codes) to be at the maximum working level.

The state of art equipment available today claims that the component is preloaded so minimally that no significant permanent damage or crack propagation occurs. Using an array of these detectors the location and size of a discontinuity may be pinpointed by triangulation. Where defects are known to exist, acoustic emission monitoring during the application of stress gives a clear indication of their behaviour, and hence relevance to structural integrity. It has been used in this capacity since the early 1980’s, often confirming that defects are indeed insignificant, i.e. voids in the centre of lap joints.

The equipment, modern PC-based instrumentation which is straightforward to use once a test procedure is defined, is portable and gives instant real time analysis and location via easy to interpret results. A colour graded visual image of the defects is provided and data is stored future examination / QC management. AE is used extensively by both civil and military aerospace service facilities including OEM's, BAe, Matra-Marconi, Saab, Aerospatiale, Boeing, Vosper Thorneycroft, DERA and construction industry contractors.

4.5 Ultrasonics

This is the most widely used NDI method for defect examination of fibre reinforced composites, regularly used to locate delamination, voids, porosity, fibre breakage, and foreign inclusions [App3 7,16,38,40,48].

Two types of ultrasonic techniques are available, based on air or liquid coupling to the laminate, the latter being most effective but requiring drying of the part before effecting a repair. Both can be used in carrying out 'through transmission' or 'pulse-echo' (signal reflection) testing, shown below.

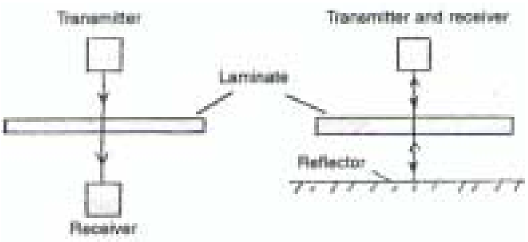

Figure 7 – Ultrasonic Transmission Types

The transmission method relies on ultrasound waves passing through the laminate to a receiver on the underside. Any damage in the part creates an air interface within the material so causing internal signal reflections, as the acoustic impedance of air is much different from that of the resin laminate itself. The measurement of reduced sound energy transmission shows the presence of flaws. However it cannot easily detect the size and depth of an irregularity, nor can it identify another defect of similar size directly below the first one.

The other major ultrasonic test, pulse-echo is similar to sonar in that a pulsed ultrasound is sent to a surface, is reflected and travels back, and the time taken is recorded. Any lengthening of the pulse travel time is indicative of an internal discontinuity in the laminate. Sensitivity can be adjusted in both techniques to aid detection of large defects whilst ignoring small anomalies or light porosity. Though small parts can be scanned manually with portable equipment, it is normal to scan using an 'xyz' table that moves the transducer across a surface and indexes it a small amount each pass. Results are viewed on a colour-enhanced display that enables easy interpretation of defects across the surface and through the component's depth [App3 55,62,64,76].

4.6 Moisture Testing

Moisture ingress is a major cause of structural delamination, and core/skin disbonds, so its coverage within a part must be accurately determined to ensure adequate removal before repair. Basic detection equipment to assess moisture levels within a component normally relies on changes in electrical conductivity. Their use would normally be restricted to laminates of glass or aramid fibre or where non-metallic honeycombs were incorporated, and proprietary meters equipped with metal prongs are readily available. Carbon fibre laminates are more difficult to assess as the fibres are already conductive, although acoustic emission and ultrasonic NDI techniques can successfully detect moisture here [App2 16,42]. Detection can also be achieved by microwave excitation of non-metallic composites and subsequent examination with laser shearography or thermography.

Before any repairs commence, parts must be assessed to be dry. In addition to suspected ingress, this would also include part surfaces that had been prepared for repair and had undergone a Water Break Test [App1], which relies on an unbroken layer of water sitting on a prepared laminate's surface to indicate the total removal of surface greases.

4.7 Eddy Current

More closely associated with flaw detection in metals, being reliant on electrical conduction for the generation of eddy currents, it has gained limited use for the analysis of carbon fibre composites. An alternating current supply cycling at about 80kHz passes through a coil and induces an eddy current flow in the fibres. Any local defects, inclusions, delaminations, fibre breaks or fibre volume fraction variations, alter the behaviour of the induced current. This change causes a reaction within the function of the search coil, and a mapped laminate area can be recorded. It can be considered complimentary to other detection techniques, but is limited to carbon fibre reinforced polymer assessment only [App2. 3,16].

4.8 Vibration Bond Testing

Mechanical Impedance analysis and acoustic flaw detection are long established processes that can determine whether a disbond or delamination has occurred in a composite structure, by measuring the change in local impedance produced by a defect when a structure is made to resonate at 1 to 10kHz. No coupling fluid is required between the structure and the transducer as these vibration techniques operate below

30kHz. Another similar instrument, a Harmonic Bond Tester, relies on the principle that a disbonded layer will resonate at higher frequencies than normal amplitudes, and will be readily detected. The range of equipment offered has a limited operating sensitivity range regarding defect size detection, but despite this has found wide acceptance in industry as a rapid inspection method [App2 13,16]. However this technique has proved to require considerable training and skill of operation, different instruments have provided different results and this procedure may require more than one supplier unit to provide a satisfactory test.

This process should not be confused with coin tapping that detects localised resonance changes, rather than changes to the structure's natural resonant frequency.

4.9 Thermography

Thermography is a fast means of inspecting large areas of a composite structure by inducing heat in to the part. Two methods exist.

The first is 'Passive Thermography' where the material under test is exposed to an intense burst of heat for a fraction of a second (flash-gun), and an infrared camera is then used to monitor the surface temperature dissipation changes. Video evidence is retained for further examination, and anomalies in pattern show the presence of defects. Two techniques can be applied, 'pulse-echo' where the camera and heat source are on the same side, or 'through-transmission' on opposite sides. The former is suited to the detection of flaws close to the surface, whilst the latter is better for deeper flaws.

'Active Thermography', the second method, creates the source of heat by vibration of the part, subjecting it to cyclic shear loading at 100-150Hz via a fatigue machine or in resonant vibration (Spate system). Where defects exist, heat is generated by free surfaces rubbing together, causing temperature differences of up to 3°C at the surface of the component.

Passive techniques are more widely applied, but performance is highly dependent on heat source used. Anisotropy and thermal conductivity of the laminate are also important as defects can be obscured that are not close to the surface. In carbon fibre laminates the thermal conductivity in the laminate plane is around 9 times that through its cross section [App3 33,57,81]. Research has shown that video evidence has enabled more precise detection of defects where short-lived changes in the temperature pattern occur.

It can be used to detect disbonds in adhesive joints, inclusions that have a widely different thermal conductivity, water ingress when frozen, and delaminations in panels. It is a more convenient process than x-ray but less sensitive than ultrasonic techniques, equipment is expensive and relies on suitable climatic conditions for effective use [App3 93,101].

4.10 Shearography

Although it has been used commercially in the US, since the late 1980's, by Boeing and NASA, laser shearography is one of the newer NDI technologies that can successfully detect damage in complex fibre composite components and GRP. It is a form of electronic holography that provides more than 350,000 adjacent real-time strain gauges on the surface of a component or structure being imaged. Shearography is very sensitive to changes in surface strain due to subsurface flaws. To highlight these a component is put under a uniform stress, using pressure, vacuum, vibration, thermal or sound techniques, and a comparison is then made of the images of the component under stress against a reference image of the unstressed part. The results are presented as black and white or colour images that clearly show the defects, stored electronically for later reference [App3 25,35,58].

This inspection technique has proven to reduce inspection procedural times on Concorde aircraft elevons to less than 30 hours, with a typical increase in defect sensitivity of more than 100%. Previous methods required more than 250 hours per aircraft. The NDI of honeycomb repairs, as well as the detection of impact damage and evaluation of repairs in composite panels, is fast and effective. Shearography can offer a great increase in the speed of inspection by allowing on-aircraft inspection without removal of parts, and the inspection of areas of several square feet in a matter of seconds [App3 66,113].

Shearography equipment manufacturers claim improved and more consistent repair flaw detection for on-craft honeycomb panel repairs. The non-homogeneity of the local structures make detection by conventional NDT methods very difficult, the local build-up of repair patches can make the use of impedance plane bond testers questionable, whilst in most cases through transmission ultrasonics is impossible and reflection slow and unreliable. Determining far side integrity from a single side is also very difficult unless vacuum loaded shearography is used.

It is believed to offer unique opportunities for on-craft detection of defects in laminate skins. This include debonds in lap joints, detection of corroded aluminium and composite honeycombs, detection of poor or improper repairs to laminates and honeycombs, and impact damage within graphite epoxy or thermoplastic laminates for production or in field situations. Fast detection area coverage is possible achieving respective NDI cost savings. Laser shearography has been successfully evaluated by the RAF, who have recently purchased three systems [App3 126], and is used to assess the structural integrity and manufacture to specification of GRP vessels produced for the RNLI. Over 240 systems are currently in use in the aerospace field, the majority being in the USA.

4.11 Laser Strain Mapping

A new portable non-contact measurement technique using Electronic Speckle Pattern Shearing Interferometry to inspect an entire surface which, with the aid of a PC and dedicated software, generates full colour qualitative and quantitative strain map data. A state-of-the-art laser creates whole field optical illumination and supporting camera systems can record large area images up to 0.5m^2 for measurement of in-plane object deformation. Visualisation of strain changes in hot, cold, static or dynamic objects is possible for all areas where maintenance of structural performance is important. This technology was developed at Loughborough University several years ago, but has only recently become commercially available. Three different models are offered to cover a wide variety of applications.

4.12 Magnetic Particle Tagging

Through the addition of small amounts of magnetic particles (size 5nm) into the composite matrix it is possible to assess the build quality of a composite by revealing fibre layout, material composition, state of cure, void content and reinforcement ratio, using conventional electromagnetic devices. Additionally, should the particles be activated by an external electromagnetic device, claims are made that selective curing, self-repair and bondline strength measurement can be achieved. The low cost ferromagnetic particles used are understood to have no detrimental effect on the performance of the composite or the matrix properties.

Measurements are made of signal outputs against control standards to assess variation of joint widths or presence of voids. Other benefits of magnetic particle tagging can include monitoring of the lamination process and eddy current inspection of the structures during service.

4.13 Electromagnetic Emission

All materials subjected to loading emit electromagnetic field pulses at radio-frequency levels when defect and crack propagation occurs. Research in Russia during the early 1990's noted that dielectric transformation processes commence due to deformation of a structure. Electrostatic charges under vibrational motion are produced on the material's surface, which then create an electromagnetic field within the material. The normally stable electromagnetic field varies when approaching defects, cracks and disbonds [App3 37,43].

4.14 Real Time Sensing

Research programmes are underway, to evaluate the effectiveness of sensors laminated into the fuselage and wings of aircraft and other highly stressed metallic and polymer composite structures [App3 3,72,97,131,136]. Reports indicate that these are taking the form of optical fibres, pzt crystals, and the carbon fibre strands themselves that change their electrical properties when strained or fractured. These systems continually record data during the life of the component, health management data can then be downloaded at every maintenance schedule, and a full life history maintained for later inspection, damage assessment and/or corrective action.

4.15 Dielectric Measurement

Research undertaken by the University of Strathclyde, on the application of high frequency dielectric spectroscopy to the examination of adhesive bonded structures, has established the ability to detect moisture ingress and joint degradation. It is hoped that current investigations will enable the dielectric technique to be used for NDE of adhesive joints in air frame structures [App3 42].

Other research being carried out in the UK by Cranfield University utilises embedded dielectric sensors and thermocouples to monitor the state of cure, in real time, of commercial grades of epoxy resin carbon fibre reinforced composites. The work is aimed to provide an intelligent closed loop control system for composite manufacturing processes such as vacuum bagging, autoclave moulding and RTM, but could equally be used to address composite repair App3 133. More accurate control of resin/adhesive cure cycles would enable its optimum mechanical performance to be achieved more consistently, and its development will improve engineers' confidence levels and provide additional data in the determination of bond line strength. However, the presence of embedded dielectric sensors within the laminate can have a negative effect on the interlaminar shear strength, causing a reduction of 15% in brittle resins and 5% with tougher grades.

4.16 Summary

Whilst it is common to use of ‘line of sight’ and ‘coin tap’ as extremely low cost, instant test indicators is commonplace, there is no one instrumented NDT inspection process that everyone uses to provide a permanent record. Some instruments are more effective than others for identification of different types of damage, whilst some materials enable clearer images to be exhibited than others. Often the NDI preference appears to be industry or OEM driven to ensure procedural specifications are met, and comparable historical test data can be generated.

In practical terms however, any test must have easy to interpret results that are accurate, meaningful, and generated fairly rapidly. Time is money when a piece of machinery or a vehicle is out of service, so effective NDI apparatus is an essential part of the plan. Equipment should be portable, robust, safe to operate, and relatively 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 portable equipment. More sophisticated laboratory based NDI conversions are available for in field operation. However, some of the techniques are limited by size, weight, and hazardous nature of the equipment required.

Those techniques preferred by the aerospace and marine and military industries for repair assessment include ultrasonics, acoustic emission, and more recently thermography, shearography and acousto-ultrasonics.

Despite all these developments the majority of NDT engineers will remain loyal to the well tried existing technologies for damage and repair assessment until the major players in the composite manufacturing industries adopt the new methods such as shearography for production quality control.

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 within composite structures would be more reliably located, and engineers, buyers and customers would operate with a greater confidence.

The one remaining major concern to industry, and the one physical condition that is still difficult to assess, is that of repair bond line strength. 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 NDI techniques to identify a solution, only mechanical destructive testing would currently appear to be the reliable method to confirm the adhesive’s strength and comparative bond line strength prior to peeling.

Service Defects	Visual	Tap Test	Acoustic Impedance	Ultrasonic	Thermography	X-Ray	Shearography	Eddy Current
Disbond	✓	✓	✓	✓	✓		✓	
Delam	✓	✓	✓	✓	✓		✓	
Impact	✓			✓		✓	✓	
Cracks	✓			✓		✓		✓
Heat Damage	✓	✓		✓			✓	
Moisture	✓			✓	✓	✓	✓	

Table 3: NDI Techniques for Composite Defects

APPENDIX 1A
COMPOSITE INSPECTION PROCEDURES

Water Break Test

Use: To ensure that a prepared repair profile is totally clean and in prime condition for resins/adhesives to achieve maximum bondline strength.

Theory: Relies on the natural surface tension characteristics of de-ionised pure water, that will exhibit an unbroken surface film on any totally clean grease free surface.

Currently a preferred procedure within aircraft repair allowing carbon, aramid, and glass fibre laminates to be thoroughly cleaned, degreased, and subsequently dried prior to application of repair materials.

Requirements: Using the appropriate power tools (air ones should have rear facing exhaust to prevent distribution of waste dusts), vibratory saws, sanding discs, localised vacuum extraction, face mask and hand protection, preparation can proceed. Following careful removal of damaged area, surrounding protective paintwork coating, and abrasion of the necessary composite laminate layers to create the required repair profile, the prepared area needs thorough degreasing.

Degreasing: This should use a recognised degreasing solvent i.e. acetone, and lint free cloths or tissue paper, with the operator wearing protective rubber or polythene gloves. A clean cell should be created with fume extraction, small quantity solvent dispensing facility, no operator smoking, disposal arrangements for used cleaning cloths.

An abrasion prepared surface should be cleaned with small acetone soaked wipes with a singular parallel motion in one direction only. Then after one pass the wipe should be thrown away, to ensure deposit removed is not returned to the surface on the re-wipe. This may seem very wasteful but is a necessity to ensure correct preparation. This single stroke wiping action, using cloths impregnated with fresh acetone from a dispenser each time, should be repeated until no further dirt stains are visually evident on the wipe.

Watering: Once this condition has been reached the prepared surface should be held in a horizontal plane, if possible, and squirted with sufficient de-ionised water to cover the repair zone. Shake or vibrate off excess and await visual evidence that water film does not form into 'beads'. If after a matter of five seconds or so, the water film is still complete then the repair preparation will be deemed acceptable. It should be noted that 'pinholing' sometimes occurs due to surface porosity and this should not be confused with the 'bead' effect.

If the water film does 'bead' then the cleaning procedure will have to be repeated with more care until a 'pass' is achieved. Aramid laminate is more difficult to clean.

Drying: Controlled drying must now be carried out to make part 'ready for repair' by placing part in a clean, temperature controlled, air re-circulating oven at a safe temperature that has been determined by taking account of the saturated vapour pressure of water for the type of component being dried. Or by laying clean lint-free moisture absorbing cloth over the prepared surface enclosing the structure or a localised region in a vacuum bag, and placing parts under a controlled heat source for a number of hours as deemed necessary. Under no circumstances should the prepared area be touched with bare skin (fingertip, etc), as natural oils will immediately be transferred, ruining the surface and necessitating a full re-clean.

Once components have been QC passed, prepared dried parts need to be issued for repair immediately, to prevent contamination. Alternatively, they should be stored between suitable lint free tissues in a dry area or bagged until the repair can be completed.

As the requirement for drying is time-consuming and adds to repair costs, alternative watering fluids have been developed to indicate surface condition and act as adhesion promoters by reacting with the abraded surface.

Industry Acceptance: Used primarily in Aircraft repair using high performance composite at present.

APPENDIX 1B
COMPOSITE INSPECTION PROCEDURES

Recommended ISO Standards for Composites Testing

Mass per unit area of prepregs	BS EN ISO 10352: 1997
Resin flow of pre-impregnates	ISO 15043
Analysis of uncured sample by DSC	BS EN ISO 11357
Degree of cure by DSC	BS EN ISO 11357
Gel time	ISO/DIW 15040
Test panel manufacture	ISO 1268: 1974 (at DIS ballot)
Test and conditioning atmospheres	BS EN ISO 291: 1997
Tensile – unidirectional	BS EN ISO 527-5: 1997
Tensile – multidirectional	BS EN ISO 527-4: 1997
Compression – unidirectional	ISO 14126 (AT FDIS ballot)
Compression – multidirectional	ISO 14126 (AT FDIS ballot)
Shear: 45 degree tension	BS EN ISO 14130: 1998
Shear modulus: plate twist	ISO 15310 (at publication)
ILSS: through thickness	BS EN ISO 1429: 1998
Flexure	BS EN ISO 1429: 1998
Mode I fracture toughness	ISO 15024 (at DIS ballot)
Fatigue	ISO 13003 (at CD ballot)
Creep testing	ISO 899
Moisture uptake/conditioning	ISO/DIS 62
Effect of water/moisture	ISO 62/175
Effect of chemicals	ISO/DIS 175
Effect of heat ageing	ISO/DIS 15034

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APPENDIX 4A
COMPOSITE REPAIR PROCEDURES

Tapered Scarf Repair Procedure Using Carbon Fibre Prepreg

Number 1a – Tapered Scarf Repair
Repair Material: Carbon Fibre Prepreg
Fabric Style 3K-70-P or similar

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced.

4. In separate dust extracted work area, if (a) then carefully cut away damage.

5. Calculate size required to effect a permanent repair, prepare scarf taper profile by marking* outline of largest repair ply and abrading away, 50:1 approx (20:1 for thicker laminates).

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar),acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance). 'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

8. Assess cleanliness visually or using Water Break Test / other method.

9. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

10. Establish the repair material specification preferred by the OEM.

11. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

12. Cut prepreg material from temperature conditioned roll, identifying and marking weave direction on its protective backing papers to coincide with the lay up orientation of the original laminate.

13. NOTE: When cutting out allow 0.5 inch/ 12mm overlap for each ply layer over the previous one. IE, if damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would be: 34,+34, 58, 82, 106, 130, 154, +178mm dia.

14. Cut film adhesive as specified (Hysol EA 9628 or similar), to 184mm in above case. This would be laid into prepared scarf, so allowing a 3mm extension of adhesive outside top cover ply.

15. Construct repair taking care to maintain weave pattern orientation and remove all backing papers as lay up is created.

16. Discounting cover plies, after laying on the adhesive film and the backing cover ply on the repair site underside, the repair plies can be laid in order with largest diameter first going smaller or in the reverse with the largest diameter last. However it is important that concentricity is maintained.

17. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

18. Once the repair plies have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

19. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

20. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

21. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

22. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

23. Return part to service.

MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4B
COMPOSITE REPAIR PROCEDURES

Tapered Scarf Repair Procedure Using Carbon Fibre and Resin

Number 1b – Wet Lay-up Tapered Scarf Repair
Repair Materials: Carbon Fibre Fabric Style 3K-70-P or similar
Resin: Epoxy

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced. If (b), contact original manufacturer for availability of tooling.

4. In separate dust extracted work area, if (a) then carefully cut away damage.

5. Calculate size required to effect a permanent repair and prepare scarf taper profile by marking* outline of largest repair ply and abrading away, 50:1 approx (20:1 for thicker laminates).

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar),acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance). This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

8. Assess cleanliness visually or using Water Break Test / other method.

9. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

10. Establish the repair material specification preferred by the OEM.

11. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and one for underside of laminate if through hole damage).

12. Using the size data generated for '5', and the pattern/ orientation required in '9', calculate the overall amount of carbon fibre fabric needed from which to cut the individual ply layers.

13. Cut sufficient carbon fibre fabric material from designated roll to enable all shapes and orientations to be cut out in a cost effective manner.

14. Weigh this fabric to establish the amount of epoxy resin mixture necessary to achieve an acceptable fibre volume fraction. Usually a 1:1 ratio of fibre and resin is accepted.

15. Weigh an equal amount of resin mixture which will comprise a% of resin + a% of hardener, and will be found in manufacturers Technical Data sheets. For example mixture for Hysol EA9390 laminating resin is 100:56, if 180gm of fibre are cut off then a resin mix comprising:

    Resin base = (180 divided by 156) x 100 = 115.38gm
    +
    Hardener = (180 divided by 156) x 56 = 64.62gm

    Note also the resin mixture 'pot life'. In this case 2 hours at 25°C. This is important so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered.

16. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface.

17. Take the cut carbon fabric and lay sheet out on a flat surface between a slightly larger area folded layer of medium/heavy gauge polyethylene film.

18. Impregnate fabric with the resin mix by opening the polyethylene fold and pouring all the liquid over the central area of the fabric. Close back the polyethylene film and using a plastic spreader, squeeze the resin front evenly from the central area radially outwards, until no dry patches are visible in the fabric. Taking care not to unduly distort the weave pattern. Mark WARP direction on film upper face.

19. Mark out individual repair plies on film upper face, and indicate warp direction on each patch.

20. Cut out repair patches. NOTE: When cutting out allow 0.5 inch/ 12mm overlap for each ply layer over the previous one. IE, if damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would be: +34,34, 58, 82, 106, 130, 154, +178mm dia.

21. Construct repair taking care to maintain weave pattern orientation and peel off all polyethylene backing films as each ply layer is put in place.

22. Start by attaching the cover ply to the repair site underside, then the repair plies can be laid in order with largest diameter first going smaller or in the reverse with the largest diameter last. However it is important that concentricity is maintained.

23. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

24. Once the repair plies have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

25. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

26. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

27. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

28. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

29. Return part to service.

* MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4C
COMPOSITE REPAIR PROCEDURES

Stepped Scarf Repair Procedure with Carbon Fibre Prepreg

Number 2a – Stepped Scarf Repair
Repair Material: Carbon Fibre Prepreg
Fabric Style 3K-70-P or similar

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced. If (b) check if tooling is available or return to manufacturer.

4. In separate dust extracted work area, if (a) then carefully cut away damage, and create through hole if necessary.

5. Prepare stepped scarf profiles by marking* outline of largest repair ply, take note of the ply orientation of the original construction and record for reference. Abrade the top layer carefully away using air powered abrasive disc wheel. Each layer is only a fraction of a millimetre thick. So, as the ply orientation usually varies for each layer, it is possible with a trained eye to halt abrasion in one area immediately the new direction/pattern becomes evident. The top layer should then be evenly removed to a band width of 0.5 inch/12mm, to reveal the next layer. At this inner diameter start to abrade away another band of the same dimensions within the first prepared step, again with care and noting breakthrough into underlayer. Halt cutting deeper and complete even step preparation around the circumference at this level. Repeat this process until all steps have been created to the desired depth.

6. Remove excess dust.

7. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

8. Clean and Degrease using environmentally friendly solvent (Fastclean or similar),acetone, or other similar degreasing agent used in your industry (Note H&S compliance). 'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

9. Assess cleanliness visually or using Water Break Test / other method.

10. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

11. Establish the repair material specification preferred by the OEM.

12. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

13. Cut prepreg material from temperature conditioned roll, identifying and marking weave direction on its protective backing papers to coincide with the lay up orientation of the original laminate.

14. NOTE: When cutting out allow 0.5 inch/ 12mm overlap for each ply layer over the previous one. IE, if damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap, two extra cover plies, and an infill ply cut to the smallest hole size that will be trapped between the back cover and the smallest repair ply, the material to be pre-cut would be: +34, 10, 34, 58, 82, 106, 130, 154, +178mm dia.

15. Cut film adhesive as specified (Hysol EA 9628 or similar), to 184mm in above case. This would be laid into prepared scarf, so allowing a 3 mm extension of adhesive outside top cover ply.

16. Construct repair taking care to maintain weave pattern orientation and remove all backing papers as lay up is created.

17. Discounting cover plies, after laying on the adhesive film and the backing cover ply on the repair site underside, the repair plies can be laid in order with the smallest diameter first, dropped into the step which accommodates it. Be careful to position each layer accurately within confines of prepared step, to prevent 'overlap doubling'.

18. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

19. Once the repair plies have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

20. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

21. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

22. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

23. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

24. Return part to service.

*MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4D
COMPOSITE REPAIR PROCEDURES

Stepped Scarf Repair Procedure with Carbon Fibre and Resin

Number 2b – Wet Lay-up Stepped Scarf Repair
Repair Material: Carbon Fibre Fabric Style 3K-70-P or similar
Resin: Epoxy

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced. If (b) check if tooling is available or return to manufacturer.

4. In separate dust extracted work area, if (a) then carefully cut away damage, and create through hole if necessary.

5. Prepare stepped scarf profiles by marking* outline of largest repair ply, take note of the ply orientation of the original construction and record for reference. Abrade the top layer carefully away using air powered abrasive disc wheel. Each layer is only a fraction of a millimetre thick. So, as the ply orientation usually varies for each layer, it is possible with a trained eye to halt abrasion in one area immediately the new direction/pattern becomes evident. The top layer should then be evenly removed to a band width of 0.5 inch/12mm, to reveal the next layer. At this inner diameter start to abrade away another band of the same dimensions within the first prepared step, again with care and noting breakthrough into underlayer. Halt cutting deeper and complete even step preparation around the circumference at this level. Repeat this process until all steps have been created to the desired depth.

6. Remove excess dust, with vacuum cleaner.

7. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

8. Clean and Degrease using environmentally friendly solvent (Fastclean or similar),acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance).'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

9. Assess cleanliness visually or using Water Break Test / other method.

10. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

11. Establish the repair material specification preferred by the OEM.

12. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

13. Using the size data generated for ‘5’, and the pattern/ orientation required in ‘9’, calculate the overall amount of carbon fibre fabric needed from which to cut the individual ply layers.

14. Cut sufficient carbon fibre fabric material from designated roll to enable all shapes and orientations to be cut out in a cost effective manner.

15. Weigh this fabric to establish the amount of epoxy resin mixture necessary to achieve an acceptable fibre volume fraction. Usually a 1:1 ratio of fibre and resin is accepted.

16. Weigh an equal amount of resin mixture which will comprise a% of resin + a% of hardener, and will be found in manufacturers Technical Data sheets. For example mixture for Hysol EA9390 laminating resin is 100:56, if 180gm of fibre are cut off then a resin mix comprising:

    Resin base = (180 divided by 156) x 100 = 115.38gm
    +
    Hardener = (180 divided by 156) x 56 = 64.62gm

    Note also the resin mixture ‘pot life’. In this case 2 hours at 25°C. This is important so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered.

17. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface.

18. Take the cut carbon fabric and lay sheet out on a flat surface between a slightly larger area folded layer of medium/heavy gauge polyethylene film.

19. Impregnate fabric with the resin mix by opening the polyethylene fold and pouring <u>all</u> the liquid over the central area of the fabric. Close back the polyethylene film and using a plastic spreader, squeeze the resin front evenly from the central area radially outwards, until no dry patches are visible in the fabric. Taking care not to unduly distort the weave pattern. <u>Mark WARP direction on film upper face.</u>

20. Mark out individual repair plies on film upper face, and indicate warp direction on each patch.

21. Cut out repair patches.

22. NOTE: When cutting out allow 0.5 inch/ 12mm overlap for each ply layer over the previous one. IE, if damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would be: +34,34, 58, 82, 106, 130, 154, +178mm dia.

23. Construct repair taking care to maintain weave pattern orientation and peel off all polyethylene backing films as each ply layer is put in place.

24. Start by attaching the cover ply to the repair site underside, then the repair plies can be laid in order with largest diameter first going smaller or in the reverse with the largest diameter last. However it is important that concentricity is maintained.

25. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

26. Once the repair plies have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

27. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

28. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

29. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

30. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

31. Return part to service.

*MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4E
COMPOSITE REPAIR PROCEDURES

Patch Repair Procedure with Carbon Fibre Prepreg

Number 3a – Patch Repair
Repair Material: Carbon Fibre Prepreg
Fabric Style 3K-70-P or similar

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced.

4. In separate dust extracted work area, if (a) then carefully cut away major damage and remove potential stress raisers, drill ends of cracks, splits etc.

5. Determine repair site size required to effect a permanent repair and prepare surfaces of laminate by light abrasion, providing approximately 25 to 50mm overlap area for patch plies over original composite.

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar),acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance).

8. 'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

9. Assess cleanliness visually or using Water Break Test / other method.

10. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

11. Establish the repair material specification preferred by the OEM. Or use a proprietary material such as Fibredux M20 Prepreg

12. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

13. Cut prepreg material from temperature conditioned roll, identifying and marking weave direction on its protective backing papers to coincide with the lay up orientation of the original laminate.

14. NOTE: If damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for two extra cover plies the material to be pre-cut would typically be: 60 underside, +60, 70, 70, 80, 90, 100, +110mm dia.

15. Cut film adhesive as specified (Hysol EA 9628 or similar), to 116mm in above case. This would be laid over prepared area, so allowing a 3mm extension of adhesive outside top cover ply.

16. Construct repair taking care to maintain weave pattern orientation and remove all backing papers as lay up is created.

17. Discounting cover plies, after laying on the adhesive film and the backing cover ply on the repair site underside, the repair plies can be laid in order with smallest diameter first going smaller.

18. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

19. Once the repair plies that equate to the number of damaged plies in the composite have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

20. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

21. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

22. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

23. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

24. Return part to service.

*MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4F
COMPOSITE REPAIR PROCEDURES

Patch Repair Procedure with Carbon Fibre and Resin

Number 3b – Patch Repair – Wet Lay
Repair Material: Carbon Fibre Fabric Style 3K-70-P or similar
Resin matrix: Epoxy resin.

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced.

4. In separate dust extracted work area, if (a) then carefully cut away major damage and remove potential stress raisers, drill ends of cracks, splits etc.

5. Determine repair site size required to effect a permanent repair and prepare surfaces of laminate by light abrasion, providing approximately 25 to 50mm overlap area for patch plies over original composite.

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar),acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance).

8. 'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

9. Assess cleanliness visually or using Water Break Test / other method.

10. Establish from the original component drawing or specification the fibre lay up pattern and orientation.
11. Establish the repair material specification preferred by the OEM. Fabric weave pattern and repair resin which has a lower cure temperature than original construction resin.

12. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

13. Cut sufficient carbon fibre fabric material from designated roll to enable all shapes and orientations to be cut out in a cost effective manner.

14. Weigh this fabric to establish the amount of epoxy resin mixture necessary to achieve an acceptable fibre volume fraction. Usually a 1:1 ratio of fibre and resin is accepted.

15. Weigh an equal amount of resin mixture which will comprise a% of resin + a% of hardener, and will be found in manufacturers Technical Data sheets. For example mixture for Hysol EA9390 laminating resin is 100:56, if 180gm of fibre are cut off then a resin mix comprising:

    Resin base = (180 divided by 156) x 100 = 115.38gm
    +
    Hardener = (180 divided by 156) x 56 = 64.62gm

    Note also the resin mixture 'pot life'. In this case 2 hours at 25°C. This is important so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered.

16. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface.

17. Take the cut carbon fabric and lay sheet out on a flat surface between a slightly larger area folded layer of medium/heavy gauge polyethylene film.

18. Impregnate fabric with the resin mix by opening the polyethylene fold and pouring <u>all</u> the liquid over the central area of the fabric. Close back the polyethylene film and using a plastic spreader, squeeze the resin front evenly from the central area radially outwards, until no dry patches are visible in the fabric. Taking care not to unduly distort the weave pattern. <u>Mark WARP direction on film upper face.</u>

19. Mark out individual repair plies on film upper face, and indicate warp direction on each patch.

20. Cut out repair patches.
21. NOTE If damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would typically be: 60 underside, 60, 70, 80, 90, 100, 110, ,+110mm dia.

22. Construct repair taking care to maintain weave pattern orientation and peel off all polyethylene backing films as each ply layer is put in place. Start by laying smallest diameter patch.

23. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

24. Once the repair plies that equate to the number of damaged plies in the composite have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

25. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

26. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

27. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

28. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

29. Return part to service.

*MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4G
COMPOSITE REPAIR PROCEDURES

Pre-Cured Doubler Repair Procedure (Adhesive Bonded)

Number 4 – Adhesive Bonded Pre-cured Doubler Repair
Repair Material: Pre-cured Carbon Fibre Fabric Patch (BAe part no….)
Adhesive: Epoxy resin Hysol, Sika 30 or equivalent

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced.

4. In separate dust extracted work area, if (a) then carefully cut away major damage and remove potential stress raisers, drill ends of cracks, splits etc.

5. Determine repair site size required to effect a permanent repair and prepare surfaces of laminate by light abrasion, providing approximately 25 to 50mm overlap area for doubler over original composite damage site.

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar), acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance). 'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

8. Assess cleanliness visually or using Water Break Test / other method.

9. Establish the appropriate Doubler size for thickness of laminate being repaired.

10. Withdraw Doubler and chosen adhesive from stock.

11. Mix a small quantity of adhesive using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface. Apply to prepared laminate, and with remainder create mechanical single lap shear test coupon.

12. Peel protective layer from Doubler, and press in place using rubber or polyethylene protected hands, care should be taken not to trap air bubbles.

13. To firmly bond and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure).

14. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

15. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

16. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

17. Return part to service.

*Any MARKING carried out should only be undertaken using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4H
COMPOSITE REPAIR PROCEDURES

Tapered Scarf Repair Procedure with Glass Fibre and Resin

Number 5 – Wet Lay-up Tapered Scarf Repair
Repair Materials: Glass Fibre Woven Roving or similar
Resin: Vinyl Ester Derakane 411-50C or compatible system

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced. If (b), contact original manufacturer for availability of tooling.

4. In separate dust extracted work area, if (a) then carefully cut away damage.

5. Calculate size required to effect a permanent repair and prepare scarf taper profile by marking* outline of largest repair ply and abrading away, 50:1 approx (20:1 for thicker laminates).

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar), acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance). 'This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

8. Assess cleanliness visually or using Water Break Test / other method.

9. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

10. Establish the repair material specification preferred by the OEM.

11. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and one for underside of laminate if through hole damage).

12. Using the size data generated for '5', and the pattern/ orientation required in '9', calculate the overall amount of carbon fibre fabric needed from which to cut the individual ply layers.

13. Cut sufficient carbon fibre fabric material from designated roll to enable all shapes and orientations to be cut out in a cost effective manner.

14. Weigh this fabric to establish the amount of epoxy resin mixture necessary to achieve an acceptable fibre volume fraction. Usually a 1:1 ratio of fibre and resin is accepted.

15. Weigh an equal amount of resin mixture which will comprise a% of resin + a% of hardener, and will be found in manufacturers Technical Data sheets. For example mixture for Hysol EA9390 laminating resin is 100:56, if 180gm of fibre are cut off then a resin mix comprising:

    Resin base = (180 divided by 156) x 100 = 115.38gm
    +
    Hardener = (180 divided by 156) x 56 = 64.62gm

    Note also the resin mixture 'pot life'. In this case 2 hours at 25°C. This is important so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered.

16. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface.

17. Take the cut carbon fabric and lay sheet out on a flat surface between a slightly larger area folded layer of medium/heavy gauge polyethylene film.

18. Impregnate fabric with the resin mix by opening the polyethylene fold and pouring <u>all</u> the liquid over the central area of the fabric. Close back the polyethylene film and using a plastic spreader, squeeze the resin front evenly from the central area radially outwards, until no dry patches are visible in the fabric. Taking care not to unduly distort the weave pattern. <u>Mark WARP direction on film upper face.</u>

19. Mark out individual repair plies on film upper face, and indicate warp direction on each patch.

20. Cut out repair patches. NOTE: When cutting out allow 0.5 inch/ 12mm overlap for each ply layer over the previous one. IE, if damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would be: +34,34, 58, 82, 106, 130, 154, +178mm dia.

21. Construct repair taking care to maintain weave pattern orientation and peel off all polyethylene backing films as each ply layer is put in place.

22. Start by attaching the cover ply to the repair site underside, then the repair plies can be laid in order with largest diameter first going smaller or in the reverse with the largest diameter last. However it is important that concentricity is maintained.

23. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

24. Once the repair plies have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

25. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

26. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

27. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

28. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

29. Return part to service.

* MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4I
COMPOSITE REPAIR PROCEDURES

Stepped Scarf Repair Procedure with Glass Fibre and Resin

Number 6 – Wet Lay-up Stepped Scarf Repair
Repair Material: Glass Fibre Woven Roving
Resin: Vinyl Ester Derakane 411-50C Grade or compatible system

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced. If (b) check if tooling is available or return to manufacturer.

4. In separate dust extracted work area, if (a) then carefully cut away damage, and create through hole if necessary.

5. Prepare stepped scarf profiles by marking* outline of largest repair ply, take note of the ply orientation of the original construction and record for reference. Abrade the top layer <u>carefully</u> away using air powered abrasive disc wheel. Each layer is only a fraction of a millimetre thick. So, as the ply orientation usually varies for each layer, it is possible with a trained eye to halt abrasion in one area immediately the new direction/pattern becomes evident. The top layer should then be evenly removed to a band width of 0.5 inch/12mm, to reveal the next layer. At this inner diameter start to abrade away another band of the same dimensions within the first prepared step, again with care and noting breakthrough into underlayer. Halt cutting deeper and complete even step preparation around the circumference at this level. Repeat this process until all steps have been created to the desired depth.

6. Remove excess dust, with vacuum cleaner.

7. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

8. Clean and Degrease using environmentally friendly solvent (Fastclean or similar), acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance). This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.'

9. Assess cleanliness visually or using Water Break Test / other method.

10. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

11. Establish the repair material specification preferred by the OEM.

12. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

13. Using the size data generated for ‘5’, and the pattern/ orientation required in ‘9’, calculate the overall amount of carbon fibre fabric needed from which to cut the individual ply layers.

14. Cut sufficient carbon fibre fabric material from designated roll to enable all shapes and orientations to be cut out in a cost effective manner.

15. Weigh this fabric to establish the amount of epoxy resin mixture necessary to achieve an acceptable fibre volume fraction. Usually a 1:1 ratio of fibre and resin is accepted.

16. Weigh an equal amount of resin mixture which will comprise a% of resin + a% of hardener, and will be found in manufacturers Technical Data sheets. For example mixture for Hysol EA9390 laminating resin is 100:56, if 180gm of fibre are cut off then a resin mix comprising:

    Resin base = (180 divided by 156) x 100 = 115.38gm
    +
    Hardener = (180 divided by 156) x 56 = 64.62gm

    Note also the resin mixture ‘pot life’. In this case 2 hours at 25°C. This is important so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered.

17. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface.

18. Take the cut carbon fabric and lay sheet out on a flat surface between a slightly larger area folded layer of medium/heavy gauge polyethylene film.

19. Impregnate fabric with the resin mix by opening the polyethylene fold and pouring <u>all</u> the liquid over the central area of the fabric. Close back the polyethylene film and using a plastic spreader, squeeze the resin front evenly from the central area radially outwards, until no dry patches are visible in the fabric. Taking care not to unduly distort the weave pattern. <u>Mark WARP direction on film upper face.</u>

20. Mark out individual repair plies on film upper face, and indicate warp direction on each patch.

21. Cut out repair patches. NOTE: When cutting out allow 0.5 inch/ 12mm overlap for each ply layer over the previous one. IE, if damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would be: +34,34, 58, 82, 106, 130, 154, +178mm dia.

22. Construct repair taking care to maintain weave pattern orientation and peel off all polyethylene backing films as each ply layer is put in place.

23. Start by attaching the cover ply to the repair site underside, then the repair plies can be laid in order with largest diameter first going smaller or in the reverse with the largest diameter last. However it is important that concentricity is maintained.

24. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

25. Once the repair plies have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

26. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

27. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

28. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

29. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

30. Return part to service.

*MARKING should only be carried out using approved pens (Sanford 'Sharpie'
Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4J
COMPOSITE REPAIR PROCEDURES

Patch Repair Procedure with Glass Fibre and Resin

Number 7 – Patch Repair – Wet Lay
Repair Material: Glass Fibre Woven Roving or similar
Resin matrix: Vinyl Ester Derakane 411-50C grade or equivalent.

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired.

2. Determine extent of damage (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced.

4. In separate dust extracted work area, if (a) then carefully cut away major damage and remove potential stress raisers, drill ends of cracks, splits etc.

5. Determine repair site size required to effect a permanent repair and prepare surfaces of laminate by light abrasion, providing approximately 25 to 50mm overlap area for patch plies over original composite.

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Clean and Degrease using environmentally friendly solvent (Fastclean or similar), acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance). ‘This should be carried out using lint free cloth or disposable wipes impregnated with clean solvent. The wiping action should be: Across repair site once, fold cloth and repeat wiping action, fold cloth to another clean area (on cloth) if possible and wipe a further section of the prepared repair site before solvent evaporates. If cloth becomes soiled immediately then dispose into a covered bin, use a new cloth and repeat degreasing until repair site no longer soils the degreasing wipe.’

8. Assess cleanliness visually or using Water Break Test / other method.

9. Establish from the original component drawing or specification the fibre lay up pattern and orientation.

10. Establish the repair material specification preferred by the OEM. Fabric weave pattern and repair resin which has a lower cure temperature than original construction resin.

11. Establish the number of layers within the original construction that need replacing. Allow one extra cover ply layer for top surface (and underside of laminate if through hole damage).

12. Cut sufficient carbon fibre fabric material from designated roll to enable all shapes and orientations to be cut out in a cost effective manner.

13. Weigh this fabric to establish the amount of epoxy resin mixture necessary to achieve an acceptable fibre volume fraction. Usually a 1:1 ratio of fibre and resin is accepted.

14. Weigh an equal amount of resin mixture which will comprise a% of resin + a% of hardener, and will be found in manufacturers Technical Data sheets. For example mixture for Hysol EA9390 laminating resin is 100:56, if 180gm of fibre are cut off then a resin mix comprising:

    Resin base = (180 divided by 156) x 100 = 115.38gm
    +
    Hardener = (180 divided by 156) x 56 = 64.62gm

    Note also the resin mixture ‘pot life’. In this case 2 hours at 25°C. This is important so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered.

15. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface.

16. Take the cut carbon fabric and lay sheet out on a flat surface between a slightly larger area folded layer of medium/heavy gauge polyethylene film.

17. Impregnate fabric with the resin mix by opening the polyethylene fold and pouring <u>all</u> the liquid over the central area of the fabric. Close back the polyethylene film and using a plastic spreader, squeeze the resin front evenly from the central area radially outwards, until no dry patches are visible in the fabric. Taking care not to unduly distort the weave pattern. <u>Mark WARP direction on film upper face.</u>

18. Mark out individual repair plies on film upper face, and indicate warp direction on each patch.

19. Cut out repair patches.
20. NOTE If damage is 10mm diameter and the laminate is constructed from 6 layers, then allowing for overlap and two extra cover plies the material to be pre-cut would typically be: 60 underside, 60, 70, 80, 90, 100, 110, ,+110mm dia.

21. Construct repair taking care to maintain weave pattern orientation and peel off all polyethylene backing films as each ply layer is put in place. Start by laying smallest diameter patch.

22. As individual ply layers are put in place, by rubber or polyethylene protected hands, care should be taken not to trap air bubbles between them, nor to distort the weave pattern.

23. Once the repair plies that equate to the number of damaged plies in the composite have all been positioned, the final protective/ largest diameter/ size cover ply should be laid in place.

24. To consolidate and cure the repair, vacuum bagging equipment must be used and a controlled cure must be achieved by the use of a localised Hot Bonder (see separate work procedure) or through the use of an autoclave facility.

25. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality.

26. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

27. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part’s maintenance records.

28. Return part to service.

*MARKING should only be carried out using approved pens (Sanford ‘Sharpie’ Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 4K
COMPOSITE REPAIR PROCEDURES

Resin Infusion Repair Procedure

Number 8 – Resin Infusion Repair
Repair Material: Vinyl Ester Derakane 411-50C grade or equivalent.

All work should be carried out in a clean dry temperature controlled environment, according to the prepreg/resin manufacturers specifications. Personal protection should be worn to protect against airborne dust, fumes, hand contamination and to prevent the prepared/ cleaned/ degreased laminate surfaces from skin contact. See Health and Safety Data Sheets. Due Care should be taken with all Hazardous & Flammable Substances

1. Assess moisture content within laminate to be repaired, and whether any contamination fluids are present.

2. Determine extent of damage, generally internal delamination, (size and depth)

3. Assess whether component can be cost effectively repaired (a), rebuilt (b), or replaced.

4. In separate dust extracted work area, if (a) then carefully cut away major damage and remove potential stress raisers, drill ends of cracks, splits etc. Drill resin inlet and bleed points at extremity of damage/repair site, to depth of delamination only, not through.

5. As this is an internally bonded repair relying on adhesion of existing material it is essential that any contaminants are removed. Ensure thorough degrease is carried out internally by flushing with solvent (Fastclean or similar), acetone, MEK, or other similar degreasing agent used in your industry (Note H&S compliance).

6. Returning to controlled clean work area. Dry laminate in a controlled manner, but limit temperature to ensure any water present is not allowed to vaporize. Solid laminates can be heated to 80°C, but honeycomb/sandwich panels must not be heated higher than 60°C, unless one complete skin has been removed to prevent further delamination. The pressure exerted by water vapour at 60°C is about 3psi (19kpa) whilst that at 80°C is about 7psi (47kpa). So drying could take several days at 60°C.

7. Assess cleanliness visually.

8. Mix the resin, using a spatula, in a disposable container/cup. Leave to stand for a few minutes to allow entrapped air bubbles to rise to surface. Note also the resin mixture 'pot life'. <u>This time is important</u> so a portable timer should be set at the work site to indicate elapsed time once the resin is mixed. No avoidable delays should encountered. Fill resin injector cartridge.

9. Clamp the vacuum resin injector over repair site, and apply vacuum. Once evacuated, open resin flow path and allow resin to be injected until witness points show laminate has been filled with resin. Close resin valve and remove injector for cleaning.

10. Maintain vacuum and allow to cure with heat assistance.

11. Once the bonded assembly has cooled and the vacuum bag consumables removed, the repair should be examined for quality. NDI inspection should be undertaken to assure bond integrity, and the presence of no inclusions, foreign objects, voids or delaminations.

12. All QC inspection sheets, material certification and batch numbers etc should be recorded, and entered onto the repaired part's maintenance records.

13. Return part to service.

*Any MARKING should only be carried out using approved pens (Sanford 'Sharpie' Permanent Marker or equivalent, which conforms to ASTM D-4236)

APPENDIX 5
IMPORTANT SAFETY PRECAUTIONS

Introduction

All composite 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 either the supplier or the user from statuary 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 FIBRE COMPOSITE LAMINATES ARE POTENTIALLY DANGEROUS AND PRIOR TO USE THE MANFUACTURER'S DATA SHEETS MUST BE READ.

Safety Precautions

Damaged composite 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. Respiratory protection is essential for those operations, such as drilling and abrading where dust exists or is generated.

COMPOSITE MATERIAL DUST IS INJURIOUS TO HEALTH, A FACE MASK MUST BE WORN AT ALL TIME WHEN DRILLING OR ABRADING COMPOSITE MATERIALS, AND THE DUST MUST BE REMOVED THROUGH A VACUUM SYSTEM AND DISPOSED OR PROPERLY AS A HAZARDOUS MATERIAL.

Eye protection, consisting of safety goggles is 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 will remove loose filaments.

Gloves polythene 'throwaway' or thin rubber 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.

Health and Safety Equipment

Respiratory Protection-Dust and Vapour Masks: Appropriate masks must be worn, depending on the hazard presented by the material being used. When sanding, dust masks must be worn. When masks are worn for protection against gases or chemical vapours, advice should be sought concerning the correct type for the hazard concerned. For example, full-face (negative pressure) masks are available and can be fitted with a wide range of filter canisters to suit gases, solvents, or particulates against which protection is required. Always consult the Material Safety Data Sheet for each hazard, and use the recommended protection.

Eye and Ear Protection: Goggles giving all-round eye protection should be worn when drilling or abrading composite materials, and when easily splashed chemicals are being used. Ear defenders should be worn for noisy processes such as grinding.

Coveralls: Overalls giving complete body protection should be worn when the situation demands that level of care. If materials being used are toxic by absorption through the skin, then coveralls providing complete protection should be worn.

Barrier Creams: These special reams should be rubbed into the hands before commencing work with resins and adhesives. Moisturising creams and barrier creams protect the skin but must be regarded only as supplements. They should be used in conjunction with gloves rather than as a replacement for gloves.

BARRIER CREAMS MUST NOT BE ALLOWED TO CONTACT ANY COMPOISTE SURFACE THAT IS TO BE BONDED.

APPENDIX 5
IMPORTANT SAFETY PRECAUTIONS

First Aid Procedures

Skin Contact

Immediately remove liquids from the skin by wiping with disposable towels, then cleanse the skin with resin-removing cream, followed by washing with warm soapy water. DO NOT USE SOLVENTS.

Eye Contamination or Irritation

Immediately flush the effected eye with eyewash bottle or fountain – or with low- pressure running water – for at least 15 minutes. Seek medical attention promptly.

Inhalation

Operators affected by the inhalation of vapour, droplets, etc., should be taken immediately into fresh air and made to rest while medical attention is called.

Clothing

Remove and isolate contaminated overalls and clothing. Launder before re-use.

Ingestion

Immediately rinse the mouth repeatedly with water. If swallowing has occurred, drink plenty of water. Seek medical attention promptly

APPENDIX 6
GLOSSARY

The list below of commonly used terms has been compiled from published glossaries located within the field of fibre reinforced plastics technology:

A-stage, B-stage, C-stage
These are the various stages in the curing process of a resin.

A-stage refers to the resin as produced by the manufacturer. The material is still liquid and can flow although it may be very viscous.

B-stage refers to the resin has cured to a degree where it is no longer liquid. Although it will not flow it is in a rubbery state and will deform when heated. Its properties are inferior to the fully cured resin. The resin in an uncured prepreg is often in this state.

C-stage refers to the final fully cured state of a thermosetting resin. It will not dissolve or melt. Full mechanical properties have developed.

Abrasion
Wear on a material surface caused by friction. Particles are removed to clean a surface to aid adhesion.

Accelerator
A material used to speed up the reaction between a resin and a catalyst. Sometimes called a promoter

Adhesion
The state in which two surfaces are held together by interfacial forces (chemical, mechanical or both).

Adhesive film
A synthetic resin adhesive in the form of a thin film. The film may be supported by a fibrous material. Used for bonding metals or cured composites and with prepregs to supply extra resin for bonding to cured materials.

Air Void
Entrapped air within and between the plies of a laminate.

Ambient Temperature
Temperature of environment around the object under consideration. Usually room temperature.

Anisotropic
Not isotropic. Having different properties along axis in different directions.

Aramid
Synthetic reinforcing material derived from polyamide (nylon). High strength, modulus and impact resistance. Examples are Kevlar and Twaron.

Autoclave
A vessel that can be pressurised with or without heat, used to consolidate and cure laminates.

Balanced Laminate
A composite laminate in which all plies at angles other than 0° and 90°. Fibre direction occurs only in equal pairs (not necessarily adjacent).

Bleeder Cloth
A woven or non-woven material used to allow the escape and absorption of excess resin during cure. It is separated from the part after cure and is not part of the composite.

Bond
To attach materials together. The attachment of an interface between an adhesive and an adherend.

Bond Strength
The amount of adhesion between bonded surfaces. A measure of the stress required to separate a layer of material from the adherend to which it is attached.

Breather Cloth
A woven or non-woven material used to provide a vacuum path over a component and to allow the escape of gases and vapours during cure. Breather and bleeder cloth are often interchangeable, remove after use.

Carbon
A non-metallic element occurring in graphite, diamond and non-crystalline forms. The basis of carbon and graphite fibres and all organic materials.

Carbon-Carbon Composite
A composite consisting of carbon fibres embedded in a matrix of carbon.

Carbon Fibre
A fibre consisting of carbon atoms arranged in a crystalline form. Often referred to as graphite fibres.

Catalyst
An active reagent used to cure some polymer resins.

Caul Plate
Plates made of aluminium or rubber used to control the shape of a repair and to even out the pressure and temperature over the surface of a repair.

Chopped Strand Mat (CSM)
Glass fibre reinforcement in short fibre form. Makes resin rich composites that minimise water uptake into composite should they become exposed.

Co-Curing
The act of curing a component and simultaneously bonding it to another component.

Continuous Filament
Individual fibre of a very small diameter drawn continuously to indefinite length.

Core
A lightweight material bonded between two skins of a composite materials to produce a thick, stiff beam.

Cosmetic Repair
Used to address score, gouge or minor abrasion through surface resin coat.

Cure
To irreversibly change the state of a polymer resin from A-stage to C-stage.

Cure Temperature
The temperature at which the chemical reaction required to cure a resin take place to completion. It may be a critical temperature or can be wide ranging.

Cure Cycle
The complete sequence of temperatures and pressures required to change a resin from its uncured state to its fully cured state.

Curing Time
The time required to fully cure the resin at the cure temperature.

Debond
Lack of bond in a joint area between two separate details resulting in failure of the adhesive bond.

Debulking
Compaction of a thick laminate under moderate heat and pressure to remove air and voids before curing.

Degreasing
The cleaning of a composite's surface or interlaminar fracture zone prior to preparation of a damaged site for repair.

Delamination
The splitting of a laminated composite along the joint lines between the layers.

Doubler
A localised area of extra layers in a laminate. In pre-cured form can be a patch repair adhesively bonded to prepared repair site.

Drape
The ability of a material to conform to complex contours.

Epoxy Resin
A thermosetting resin containing the chemical component known as an epoxide group. Offers more flexibility than polyester and some other resins.

Exotherm
The evolution of heat during cure.

Fabric
A woven reinforcing material, comprising two or more sets of yarns interlaced in such a way that the elements pass each other at right angles.

Fatigue
Failure due to repeated applications of stress.

Fibre
A general term used to refer to a filamentary material. The term's fibre and filament are often interchanged.

Fibreglass Reinforcement
A reinforcement fibre consisting of monofilaments of glass.

Fibre Orientation
The direction of the fibres in a composite.

Filament
The smallest unit of fibrous material which are normally gathered together to form strands.

Fill
See weft.

Filler Ply
A layer of reinforcing material used in composite repair to fill a space or increase local thickness in a composite.

Film Adhesive
See adhesive film.

Foaming Adhesive
An adhesive strip used to join honeycomb. It foams during cure to fill spaces within the joint.

Gel coat
A resin used to produce a particular surface finish, often a protective layer, on a fibre-reinforced composite.

Gel Point
The point at which the properties of a curing resin take on rubbery characteristics.

Gel Time
The time taken for the resin to reach the gel point after addition of the hardener or catalyst.

Glass Cloth
Glass reinforcing fibres in the form of a woven cloth.

Glass Fibre
A reinforcing fibre made from filaments of glass.

Graphite Fibre
Fibres consisting of carbon in the form of graphite.

Hand Lay-Up
Production of a composite in an open mould by impregnating and bonding together layers of reinforcing materials by hand.

Hardener
A substance added to a resin to cause and take part in curing. The hardener becomes a constituent part of the cured resin.

Inhibitor
A substance added to a resin to retard the curing process.

Interface
The boundary between the individual, physically distinguishable constituents of a composite.

Interlaminar Shear
Shear strength between adjacent plies of laminate.

Laminate
A composite consisting of layers or plies of reinforcing materials bonded together.

Mat
A reinforcing material consisting of randomly orientated filaments or strands.

Matrix
The essential homogenous material in which the fibre reinforcement is embedded.

Modulus
The stiffness of a material.

NDE
Non destructive evaluation.

NDI
Non destructive Inspection

NDT
Non Destructive testing.

Orientation
The alignment of the fibres in a composite.

Out Life
The time that a prepreg or adhesive film remains useable after removal from its recommended storage conditions.

Peel Ply
A woven non-stick material, often nylon fabric, used on the surface of a composite during cure. On removal it produces a rough surface suitable for subsequent bonding or other surface treatment.

Plain Weave
Fabric weave in which each warp and weft fibre passes alternatively over fibres at right angles.

Ply Orientation
The direction of a ply in a laminate with respect to a standard ply orientation convention.

PAN
Polyacrylonitrile. The starting material in the production of carbon and graphite fibres.

Polymer
An organic material with a long chain molecular structure produced by the repeated combination of smaller chemical units.

Polymerisation
The chemical process used to produce a polymer.

Porosity
Voids evident within a laminate. Can be caused by trapped air or chemical gassing.

Pot Life
The length of time that a resin remains useable after addition of the catalyst or hardener.

Potting Compound
A resin system containing a thickening agent used in joining honeycomb, edge filling, holding in fasteners etc.

Prepreg
A reinforcing fibre impregnated with a resin/hardener system by the manufacturer. To provide a controlled fibre/resin content. Usually supplied at B-stage and stored at low temperatures to increase shelf life.

Ramping
The gradual increase in temperature during a cure cycle.

Ramp Rate
The rate at which the temperature is increased during ramping.

Release Agent
A material used to prevent adhesion during curing. Should be used with extreme care to prevent repair site contamination and breakdown of important bond areas.

Release Film
A plastic film used as a release agent.

Resin
A flowable polymer material which can be converted to a solid state by application of heat or addition of a chemical hardener or catalyst.

Resin Content
The proportion of resin in a composite. Presented either by % weight or % volume.

Ribbon Direction
In a honeycomb the direction of the sheet material in relation to the cells.

Room Temperature Cure
The cure of a resin at low temperature although not necessarily at ambient temperature. Various bodies define room temperature differently. May be as high as 80°C.

Roving
A number of continuous yarns or strands collected together without twisting.

Sandwich Panel
A composite panel consisting of two composite skins separated by a relatively thick lightweight core.

Satin Weave
A reinforcement weave style in which each weft strand passes over a number of warp strands and vice versa.

Scarf Joint
A joint between two components by bonding them together over a gradually tapering section.

Shelf Life
The length of time that a resin or prepreg system can be stored before the flow and tack properties of the liquid resin or the mechanical properties of the cured resin deteriorate beyond the applicable specification requirements, or remain suitable for their intended functions.

Size
A surface treatment of reinforcing fibres to aid processing or handling. Usually removed in the final stages of production.

Strand
An untwisted collection of fibres or filaments cut into short lengths.

Syntactic foam
Foams made by mixing hollow spheres of glass or plastic with a polymer resin. Used to create a constant adhesive thickness in sandwich panel construction.

Tape
A reinforcing material in which all the fibres are aligned in one direction. Usually less than 12 wide.

Thermocouple
A device consisting of two dissimilar wires joined together. When heated it produces an electrical signal proportional to the temperature.

Thermoset
A polymer which can be irreversibly cured by the action of heat or addition of a hardener or catalyst.

Tow
Equivalent to roving. A loose, untwisted bundle of filaments.

Unidirectional
Having all reinforcing fibres in the same direction.

Vacuum Bag
A plastic bag used to enclose a component during cure so that air and volatiles can be removed and for application of atmospheric pressure to the component.

Vinyl esters
A class of thermosetting resins.

Void
Entrapment of air or gas in a component.

Volatiles
Gaseous materials produced during the curing process.

Warp
The yarn running length-wise in a woven fabric.

Water Break Test
A test used to assess the cleanliness of a prepared surface. A clean surface will maintain a continuous film of water.

Weft
The yarn running across a woven fabric.

Wet Lay Up
Production of a laminate using fibrous reinforcements and liquid resins.

Woven Roving
A heavy fabric made by weaving rovings.

Yarn
An assembly of twisted filaments, fibres or strands.