Report on Repair Techniques for composite parts of Wind Turbine blades

Draft

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1. INTRODUCTION

Wind turbine blades made of composite materials suffer from flaws, which are generated during construction and/or service life. Within the framework of EC funded research project OPTIMAT BLADES (ENK6-CT2001-00552) Work Package 11 (WP11) deals with the investigation of suitable techniques for repair of flaws found in W/T blades. This document provides a survey of current repair techniques applied on defected composite material parts in a more general sense with the objective to serve as the baseline for the definition of the repair types for W/T blades to be examined during the project.

Current repair practices have been based on very conservative damage limits [1]. In many cases the repair designs are inappropriate [1]. For restoration of the structural integrity of damaged composite parts the repairer needs to be able to model the damage and conduct at least, simple stress analysis to determine the degree of loss of structural integrity. This will lead to the best repair scheme design.

The recommended 10 step repair process is shown in Table 1.

Table 1 The ten steps of composite structural repair

Step	Practice
1	Find the damage
2	Assess the extend of the damage
3	Analyse damage stress state
4	Design repair scheme
5	Remove damage and prepare structure
6	Fabricate repair scheme
7	Apply repair scheme
8	Conduct post-repair inspection
9	Document repair
10	Monitor repair zone

2. DAMAGE TYPES

Although composite structures offer many advantages over conventional materials, they are prone to a wide range of defects and damage, which can significantly reduce the residual strength and/or stiffness of the structure. A defect, also known as a discontinuity, flaw or damage, is defined as, "any unintentional local variation in the physical state or mechanical properties, which may affect the structural behavior of the component" [1]. Defects may be present initially in the structure due to faulty manufacture, or even due to the inherent variability of the composite material or may be introduced during service due to damage resulting from mechanical contact or environmental effects [2].

According to the Detailed Plan of Action (DPA) for WP11 of the OPTIMAT project, involved partners are mainly interested in defects found during or immediately after production. Therefore these types of flaws will be addressed in more detail in the sequel [3].

The 51 known separate defect types found in composite components are listed alphabetically in Table 2 [1].

Table 2 Types of defects found in composite materials

Bearing surface damage	Blistering	Contamination	Corner/Edge splitting
Corner crack	Corner radius delaminations	Cracks	Creep
Crushing	Cuts and scratches	Damaged filaments	Delaminations
Dents	Edge damage	Erosion	Excessive ply overlap
Fastener holes	Fiber distribution variance	Fiber faults	Fiber kinks
Fiber/matrix debonds	Fiber misalignment	Fracture	Holes and penetration
Impact damage	Marcelled fibers	Matrix cracking	Matrix crazing
Miscollination	Mismatched parts	Missing plies	Moisture absorption
Overaged prepreg	Over or under-cured	Pills or fuzz balls	Ply underlap or gap
Porosity	Prepreg variability	Reworked areas	Surface damage
Surface oxidation	Surface swelling	Thermal stresses	Translaminar cracks
Unbond or debond	Variation in density	Variation in fiber volume ratio	Variation in thickness
Voids	Warping	Wrong materials	

Although there are different aspect criteria by which these types of defects can be categorized, in this document defects are classified into four main groups, depending on the defect type size, location and cause. These are delaminations, transverse matrix cracks, holes and design variance. Delaminations are cracking between the ply interfaces, or interlaminar fracture. Transverse matrix cracking is matrix cracks within a ply. Holes are cuts or breakage of fibers. Design variance refers to the changes in the engineering parameters. Another classification according to the cause of defects can be found in [2]. Table 3 lists the 51 types of defects under the headings of delaminations, matrix cracks and holes according to [1].

Industrial partners in WP11 expressed their interest in following types of defects and their repair: delaminations, sever fiber misalignment (wrinkle, fold) and dry spots, while cracks are considered in the third place [3]. On Table 3 defect types of interest to the partners in the project are marked bold. Folding of plies is a combination of fiber kinking, delamination, excessive ply overlap (region that supports the fold) and missing plies (region that does not have the ply). Dry spot on the other hand could be set under the category of matrix cracks.

Table 3 Generalized defect types

Delaminations	***Matrix cracks***	***Holes***
Bearing surface damage Blistering Contamination Corner/Edge splitting Corner radius delamination **Delamination** Unbond or debond Edge damage Fastener holes Fiber/matrix debond Holes and penetration Pills or fuzz balls Surface swelling	Bearing surface damage Contamination Corner/edge crack **Cracks** Edge damage Matrix cracking Matrix crazing Porosity Translaminar cracks **Voids**	Bearing surface damage Crushing Cuts and scratches Fastener holes **Fiber kinks** Fracture Holes and penetration Reworked areas Surface damage

Under the category of Design variance types of defects there are defects that are incorporated in the design of a blade by using material partial safety factors, there are others that can be avoided, mainly during construction by applying strict inspection rules but there are still some remaining that are unavoidable.

Table 4 Design variance types of defects

Taken into account	***Avoidable***	***Unavoidable***
Creep Fiber distribution variance Erosion Moisture absorption Prepreg variability Surface oxidation Thermal stresses Variation in fiber volume ratio Variation in thickness Variation in density	Damaged filaments **Excessive ply overlap** **Missing plies** Mismatched parts Overaged prepreg Over or under-cured Ply underlap or gap Wrong materials	Dents Fiber faults **Fiber misalignment** Impact damage Marcelled fibers **Miscollination** Warping

An extensive analysis of the various failure modes and mechanisms of all the defect types concluded, for the sake of adequate modeling, that the principal damage types are: transverse matrix cracks, holes and delaminations. This aligns well with the generalized defect types, as well as with the defects of interest to the project. Of equal importance in damage analysis is the damage progression of the principal defects. This is summarized as follows:

(a) Multiple cracking is the first stage of damage, where the damage pattern is random and scattered over the laminate.

(b) The second stage of damage progression is the initiation of delaminations, or damage localization. Here the damage develops at preferred sights, such as free edges or ply interfaces.

(c) The final fracture is often multimoded with severe cracking; however, fiber fracture appears to be the controlling factor.

According to the DPA [3] the damage location within the framework of the OPTIMAT project will be limited to parts of the primary structure, e.g the girder part of the blade and not the sandwich parts including foam. Under this respect the edge defects and sandwich structures will not be addressed in this document in the same detail as the rest of the defects.

3. FINDING THE DAMAGE

NDI methods are employed in the damage analysis and repair design process of composite structures in three ways:

(1) Damage location;

(2) Damage evaluation, i.e. type, size, shape and internal position; and

(3) Post-repair quality assurance.

The first and most important activity in the damage analysis and repair design process is to identify the damage. Assessment of the damage is initially achieved by visual inspection. This localizes the damaged area, and is then followed by a more sensitive NDI method, which maps the extent of any internal damage. Detailed NDI is very important when dealing with composite structures, particularly because the majority of the damage is usually hidden within the composite structure.

A number of NDI techniques are currently available for identifying damage in composite structures, such as: visual, including optical magnification, acoustic methods, like the tap test, ultrasonic methods, such as A-scan and C-scan, material property changes, especially stiffness. NDI methods and their applicability to detecting damage in composite materials are not the main issue of this document. However, the appropriate application of NDI techniques is of major importance to assure the proper repair assessment, therefore, the two tasks are interconnected.

4. DAMAGE MODELLING AND ANALYSIS

Damage analysis of composite structures is based on the stress state around the damaged area. The estimated stress state is then compared with the component's ultimate strength in some form to determine the severity of the damage. This approach tends to be conservative, but will provide the engineer with an idea of what type of repair scheme needs to be designed, i.e. cosmetic, structural, or something in between. The three generalized defect types that are of most concern as explained in the above are transverse matrix cracks, delaminations and holes.

A local stiffness loss is attributed to transverse matrix cracks. Whereas, structural instability under compressive or shear loading is of greatest concern in the presence of delaminations. With holes, a laminate experiences a strength reduction due to a stress concentration effect.

A review of the 10 step repair process as shown in Table 1, suggests that following damage location assessment, the stress state of the damaged area should be determined. This is then followed by the repair scheme design. Current repair methodology tends to bypass the damage analysis step and design the repair based on past experience or similar structural damage. However, to ensure that the most appropriate and cost-effective repair is selected and designed, the stress state of the damage area should be determined. The problem is to assess whether these flaws have reduced the residual strength of the structure below an acceptable level or whether the flaws may grow in service and thus, at some stage, reduce the residual strength of the structure below an acceptable level.

In composite materials, particularly at free edges such as holes or other defect, the stress state is truly three dimensional. The interlaminar stress components, σ_z, τ_{xz} and τ_{yz} can be difficult to estimate or measure, although necessary in the complete stress state analysis. As a simplification only in-plane stresses will be analyzed and by utilization of the current design variables they will provide the sufficient damage tolerance required for these interlaminar stresses. Furthermore, under tension loading, the flaws are usually not a serious problem, ignoring possible environmental damage, since load redistribution can occur and growth is fairly slow [2]. However, if peel stresses can develop, which is particularly the situation in compression loading, the flaws can grow very rapidly and result in catastrophic buckling failure.

4.1. Matrix crack analysis

As already mentioned, transverse or intralaminar matrix cracks have little effect on the strength of fiber dominated laminates, but they can reduce local stiffness. Assessment of the local loss of stiffness can simply be achieved by using degraded matrix stiffness and strength properties of the damaged plies. Generally, a 65%-90% reduction can be applied directly to ply transverse properties, or used in micromechanics analysis [4]. Similar reduction should be applied to the ply's compressive strength in the fiber direction [4]. If the stiffness reduction is severe, particularly when the laminate is subjected to compressive loads and fatigue cycling, then delamination may be initiated. Severe stiffness loss may lead to local buckling. A check of the local buckling criticality should be performed, as described in following section.

4.2. Delamination analysis

Stress state near a delamination is a very demanding task, as is recognized in literature. However, it is the compressive strength, which is severely reduced. Under compressive loading, crack growth generally follows sublaminate buckling. As an initial estimate of potential delamination crack growth one should determine the stability of the sublaminate under design loading conditions. Three approximate, but easy to apply methods are presented in [1] for sublaminate buckling analysis of delaminations, based on classical lamination theory and applying simplification assumptions. At present time, the rule of thumb is that delaminations below about 20-30mm in diameter will not reduce residual strength, or grow under compression-dominated fatigue loading, when subjected to strains below about 4000 microstrain, which is close to the present ultimate allowable strain and may therefore, be left unrepaired. Larger delamination, particularly those in critical areas exposed to high compression strains, should be repaired.

4.3. In plane hole analysis

The in-plane stress analysis of holes requires knowledge of the laminate stiffness matrix, hole geometry and applied far-field stresses or strains. The more widely used methods are discussed in [1], with the simplified method being the most promising when considering that engineers should be able to perform damage analysis even in the field. Interested reader is referred to this document for more details.

5. REPAIR DESIGN AND ANALYSIS

5.1. Repair criteria

A rational basis is required for assessment of the seriousness of flaws in composite components. Three basic decisions are possible:

(a) The defect is negligible, in which case it may be disregarded apart, perhaps, for some cosmetic treatment;

(b) The defect is not negligible, but the component is repairable; or

(c) The component is not (economically) repairable and therefore must be replaced.

The decision making process must allow for the nature of the stressing and the environment, the cost of repair compared with replacement (including the loss of availability of the wind turbine), the reliability and efficiency of the repair and the consequences of failure.

The repair design is often driven by engineering requirements other than stress analysis. These design drivers include the following:

(a) Availability of repair facilities, including tools, equipment and materials, as well as the level of repair authorization.

(b) The type of damage found has significant influence on the structural design of the repair. Damage analysis will indicate the degree of structural degradation or the significance of transverse matrix cracks, delaminations and holes.

(c) Repair done on site or in manufacturers facilities will involve a certain level of compromise between adequate strength/stiffness restoration and wind turbine down-time and labor/material costs.

(d) Accessibility of the damaged area influences design simplicity and repair scheme application methods.

The basis of the repair design follows logical repair criteria. Some of the parameters of repair criteria, which should be usually addressed during an analysis, are listed in Table 5.

Table 5 Repair criteria

#	*Criterion*	*Assessment*
1	Static strength and stability	Full versus partial strength restoration; Buckling and deformation resistance
2	Repair durability	Fatigue load spectrum; Corrosion resistance; Environmental degradation
3	Stiffness requirements	Deflection limitations; Flutter and other aeroelasticity effects; Load path variations
4	Aerodynamic smoothness	Fabrication techniques; Structural performance effects
5	Weight and balance	Size of repair on the parent structure; Mass balance effect
6	Operational temperature	Low and high temperature requirements Effects of extreme temperatures
7	Environmental effects	Types of exposure; Effects on matrix and adhesives
8	Related systems	Lightning protection; Aerodynamic brakes and system operation
9	Costs and scheduling	Down-time; Facilities, equipment and materials; Personnel skill levels; Materials handling capabilities; Safety precautions
10	Other characteristics	

5.2. Repair analysis

5.2.1 Matrix cracks

As it is suggested, matrix cracks have little effect on a component's structural strength, but can cause local stiffness losses and potential instability problems under compressive and shear loading, two repair types are recommended:

(a) If the matrix cracks are insignificant as a damage type on the structural integrity of the composite laminate, but they are exposed to the surface, then only a filling/ sealing type repair is warranted. This type of repair will ensure that moisture is excluded from the damaged area.

(b) If damage analysis indicates that local structural instability is likely, then the damaged region is filled and sealed with an external patch to restore local stiffness. The effective restored stiffness should be equivalent to that of the component's undamaged stiffness [1]. Using following equation:

$$E_{Restored} = \frac{E_{lam} h}{t_r} \qquad \text{Eq. 1}$$

where E_{lam} is the laminate effective principal stiffness, h is the laminate thickness and t_r is the thickness of repaired region. That means, that the restored stiffness is equal with the effective patch stiffness plus the degraded stiffness, or in a mathematical expression [1]:

$$E_{Restored} = \frac{E_p t_p + E_{dam} t_{dam} + E_{undam} t_{undam}}{t_r} \qquad \textit{Eq. 2}$$

where E_p and t_p is the patch stiffness and thickness, respectively, E_{dam} and t_{dam} is the corresponding stiffness and thickness of the degraded region and E_{undam} and t_{undam} is the stiffness of the undamaged region.

For both types of transverse matrix crack repair scheme:

(a) the damage is not cut-out, because load-carrying fibres are still in place,

(b) the local damaged region is dried out prior to repair application, particularly if a heat-cured repair scheme is applied and

(c) a low viscous filling/sealing resin is used.

Fig. 1 schematically shows the repair applied to matrix cracks in a composite structure by filling and using a sealing patch.

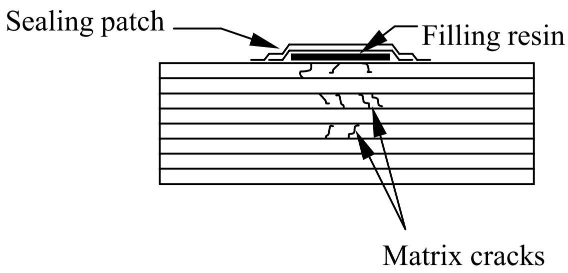

Fig. 1 Repair of matrix cracks by filling and doubler patch

5.2.2 Delaminations

Although there is an overall strength loss due to delaminations, this occurs because of stiffness degradation. The strength loss is due to a combination of increased net stresses, local warping of the sublaminate due to an unsymmetrical lay-up and local buckling. The delaminations are cut out down to the depth of the deepest delamination and either a scarf or plug/patch repair scheme is applied. Fig. 2 displays the two repair systems described in detail in following sections.

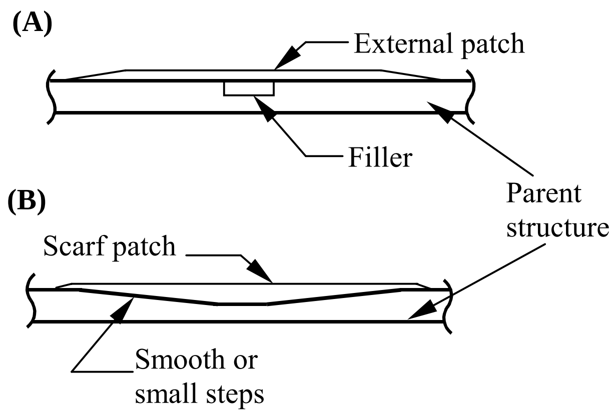

Fig. 2 Plug/patch (a) and scarf (b) repair systmems

5.2.2.1 Scarf repair scheme

The scarf repair of delamination damage is designed such that the lay-up matches that of the plies removed. Notes for scarf repairs [1]:

- The scarf angle varies between 1º and 3º.
- The repair patch is stepped and has the same lay-up as the parent laminate.
- A two ply external patch, usually ±45º plies, is used as an environmental seal.
- The repair patch is co cured in place because it is most likely unbalanced and unsymmetrical.

With simple analysis, when the patch and parent laminate stiffnesses are balanced and the thermal coefficients of expansion matched, the shear and normal stresses are given by the following equations respectively [1]:

$$\tau = \frac{P\sin(2\theta)}{2t} \qquad \textit{Eq. 3}$$

$$\sigma = \frac{P\sin^2(\theta)}{t} \qquad \textit{Eq. 4}$$

The allowable load in the joint is given by the next relationship [1]:

$$P_{all} = E\varepsilon_{all}t = \frac{2t}{\tan\theta} + D \qquad \textit{Eq. 5}$$

where t is the laminate thickness and D is the hole diameter (equal to the delamination pattern).

5.2.2.2 Plug/Patch repair

The plug/patch repair scheme requires the load to be transferred around the hole through the external patch. Notes for the plug/patch repair scheme:

- The lay-up sequence should be identical to that portion of the parent laminate below the repair plug.
- Structural analysis of this joint is based on that of a double-strap joint, as explained in a following section.

None of the delaminated plies are removed. The repair scheme is to adhesively bond a doubler patch over the delaminated region. The required repair scheme is to stiffen the delaminated region by an adhesively bonded patch. Determination of the patch stiffness is based on the analysis with the above Eq. 1, but here the stiffness of the sublaminate and patch needs to be such that the critical buckling load is greater than the applied design allowable load [1]. Or more simply ensuring that the stiffness of the patch is equivalent to the undamaged stiffness, calculated by:

$$E_p = \frac{E_{lam} h}{t_p} \qquad \textit{Eq. 6}$$

5.2.2.3 Edge delamination repair

With an edge delamination the first requirement of the repair scheme is to seal the edge from further moisture absorption. Again a low viscous resin is used. Local in-plane stiffening of the edge is more difficult since the out-of-plane forces which cause delamination growth are still present. The most effective repair design is to simply reinforce the out-of-plane direction with a fastener, stitching or capping patch. Since the out-of-plane stresses are much lower than the in-plane, a capping patch is all that is required. The capping patch is made composite cross-ply of thickness about 1mm and overlap length on the upper and lower surface extending 25mm beyond the depth of the delamination.

5.2.3 Holes

Three fundamental repairs are required for holes. These are classified as low, moderate and full strength restoration, and depend on the degree of the strength loss in the structure as discussed in previous section.

5.2.3.1 Low strength restoration hole repairs

When the hole in the laminate has minimal strength degradation the general repair is a plug/ patch scheme, but with a non-load bearing external patch.

5.2.3.2 Moderate strength restoration hole repairs

When damage analysis of a hole indicates that there is moderate strength degradation, i.e. the current level of damage tolerance is significantly reduced, but catastrophic failure would only occur with severe overload, then a plug and structural external patch is recommended. The plug is of low modulus material so that it will not attract load. The design of the patch follows a simple double-lap joint method such that only half a double-lap joint is designed, acknowledging:

(a) supports for bending resistance;

(b) a tapered patch is used to reduce peel, particularly when the thickness of the patch is greater than 1mm;

(c) the patch stiffness and thermal expansion coefficients are matched to those of the parent laminate; and

(d) the hole is not tapered.

Based on the idealized elastic-plastic adhesive stress/strain curve, the load-carrying capacity of the joint is given by the following equation [1]:

$$P = 2\sqrt{\eta\tau_p\left(\frac{\gamma_e}{2}+\gamma_p\right)Et} \qquad \textit{Eq. 7}$$

where P is the load per unit width, η is the adhesive thickness (nominally 0.125mm), Et is the effective stiffness of the patch or parent laminate, τ_p is the plastic shear stress and γ_e and γ_p is the elastic and plastic respectively shear strain.

The ultimate load per unit width of the patch is given by the following relationship:

$$P_{ult} = E\varepsilon_{ult}t \qquad \textit{Eq. 8}$$

where ε_{ult} is the ultimate design strain, which for composite structures is typically 4000$\mu\varepsilon$.

The patch overlap length is given by the next equation [1]:

$$l_{over} = \left[\frac{P_{all}}{\tau_p}+\frac{2}{\lambda}\right]f_s \qquad \textit{Eq. 9}$$

where $\lambda = \sqrt{2G/\eta Et}$, with $G = \tau_p/\gamma_e$, $P_{all} = P_{ult}/1.5$ and f_s is the factor of safety, typically 2, which depends on the degree of difficulty of the repair, the effects of thermal and stiffness mismatch and if the single strap is unsupported.

5.2.3.3 Full strength restoration repairs

When the hole causes significant reduction to the laminate strength, a fully structural restoring repair is required. The repair will be a scarf (stepped-lap) adhesively bonded patch for thinner structures, or for thicker sections a bolted patch. Initial analysis of a scarf joint will indicate when a bolted patch is preferred. For the scarf adhesively bonded patch repair the scarf angle is less than 3° and the analysis is performed as described in previous section.

The analysis of a bolted repair follows the methodology of a mechanically fastened joint using ultimate load per unit width and Eq. 8. Several methods of bolted joint analysis are available. However, the bolted repair analysis is complex in derivation and less applicable to repair of wind turbine rotor blades.

6. REPAIR TECHNIQUES

The repair approaches can be broadly divided into nonpatch, usually for minor defects, and patch, usually for more major defects and damage. However, these two procedures may be employed in combination for some types of repair. In general for composite material structures there are four basic levels of generic repair designs [1]. Although, not all of them are applicable to wind turbine blades, these are listed below:

(a) Non-structural or cosmetic repairs. Filling and sealing the damages area where damage significance is minor, but environmental protection is necessary, is a cosmetic or non-structural repair.

(b) Semi-structural repair. Filling the internal cavity with an adhesive foam or core replacement and applying a doubler patch to the damaged area is a semi-structural repair. The doubler patch can be non-load-bearing, either load-bearing or have some intermediate load carrying capacity.

(c) Adhesively bonded structural repair. A flush patch adhesively bonded over the damaged area, is a major structural repair utilizing a scarf of stepped-lap joint. The flush patch is generally applicable to thin skin structures only.

(d) Mechanically fastened structural repair. Another structural repair is the bolted patch. This is used on primarily thick structural components.

6.1. Repairs to minor structural damage [2]

6.1.1 Injection Repair

Resin injection repairs are used for matrix cracks, minor delaminations and disbonds. The effectiveness of this approach depends on whether the defect arose during manufacture or was due to mechanical damage during service. Due to the local lack of bonding pressure or contamination of the bonding surface, manufacturing flaws have a surface glaze that must be removed to ensure high bond strength. This cannot be achieved for internal surfaces; thus, these repairs are unsatisfactory. In contrast, internal flaws caused by mechanical damage have a surface that can be bonded reasonably effectively, provided contamination has not occurred, for instance, with moisture (which can be removed by drying) or service fluids, such as hydraulic oil.

The injection procedure involves the formation of several injection and bleeder holes that must penetrate to the depth of the defect; this requires accurate non-destructive inspection. If the defect is not penetrated, the resin cannot enter the void; if the hole is too deep, damage will occur to the material below the void and the injection may be inefficient. The resin is usually injected after preheating the repair area; prolonged heating may be required to remove moisture. Resin is injected by means of an air-gun, until all of the holes have been treated; then the holes are temporarily sealed with a layer of protective tape. Finally, pressure is applied to the repair area to improve the mating of adjacent regions and to improve or maintain contour. The resin is allowed to gel at room temperature, usually followed by a post cure at elevated temperature.

6.1.2 Filler or potting-type repairs

Potting repairs are made by filling the defective region with a filler compound; minor indentations may be filled in this way, provided NDI has ensured that no serious internal matrix cracking or delaminations are present. In the case of lightly loaded foam panels, such as in the trailing edge region, potting repairs may be made to stabilize the skin and seal the damaged region.

Damage in attachment holes, such as minor hole elongations or wear damage, may be repaired with machinable potting compound. Filling the hole with machinable potting compound and then redrilling can rectify misallocated or oversized holes.

6.2. Repairs for structural restoration [2]

Patch repairs are generally employed to repair major damage and essentially involve replacing the lost load path with new material joined to the parent structure. Thus, the repair is best considered as a joint for the purpose of design.

6.2.1 Bonded external patch (plug/patch repair)

In this approach, the damaged region is removed, leaving a straight (or preferably tapered) hole and over this region a patch with tapered (or stepped ends) is bonded to the parent laminate. This repair configuration is similar to that of a tapered single-overlap joint; the taper is most important to reduce peel and shear stresses that would otherwise cause failure of the patch. However, a taper is not required for patches of only a few ply thickness. External patches can be employed reasonably successfully, depending on the stressing requirements of the area, to repair skins of thickness up to about 16 plies. This type of repair will be the most widely employed, since external patches are relatively easily applied under field conditions. Strength recoveries of 50-100% of ultimate allowables of the parent material can be achieved, depending on the laminate thickness.

The main problem with external patches is that, there is an eccentric load path that results in quite severe bending in the patch and peeling stresses in the adhesive and composite. Out-of-plane bending under compressive axial loads can also significantly reduce the buckling stability. However, these effects are greatly reduced if the patched region is supported by a substructure, such as foam core, that reacts out the bending.

Several options exist for the patch; it may be made with similar ply configuration of the parent laminate; or it could be made with a quasi-isotropic lay-up or a standard layup (to reduce the danger of lay-up and application errors, in which case it would require being thicker than the parent laminate.

The patch may be: (1) formed over the parent laminate from pre-preg tape cut to shape and then co cured with the adhesive, (2) procured in layers and bonded to the parent laminate during the repair with interleaved layers of adhesive, or (3) preformed to shape and then bonded to the parent material in a subsequent operation. This last option produces the best patch properties; however, since the preformed patch is not compliant, serious fitting problems may arise on curved surfaces.

6.2.2 Flush patch repairs (scarf repair)

The flush patch repair configuration is similar to a single scarf joint, and therefore, has the benefit of a nearly uniform shear stress distribution in the adhesive layer. In addition, due to the lack of eccentricity in the load, the patch peel stresses are low. Therefore, flush repairs are highly efficient and are particularly suited to external repairs of thick laminates because of the unlimited thickness of material that can be joined and the smooth surface contour that can be produced.

However, flush repairs are much more difficult and time consuming to apply than external patch repairs and so will usually be employed only under depot or factory conditions. A further, and significant, disadvantage of flush repairs is that they require taper angle of about 1:18. Single-sided flush patches can be employed to repair part-through or full-penetration damage. A part-through flush patch, may, as an example, be used to repair a delaminated region in a thick laminate when injection repair is not considered adequate; the material above the delamination is first ground away to leave a recess with the appropriate taper.

Flush repairs are usually based on patches with a ply configuration similar to the parent material. These patches are generally co cured to avoid the severe fit-up problems encountered with procured patches. To cure the patch and adhesive, pressure may be applied by a vacuum bag - heater blanket procedure. Alternatively, in a factory, temperature may be applied in an oven in combination with a vacuum bag pressurization system or, best of all where possible temperature and pressure may be applied in an autoclave.

6.3. Smart repair systems

Currently in a premature state are several studies for the use of smart repair systems for polymer matrix composites. These systems indent to be applicable on situations of delaminations and microcracking induced due to impact. The underlying technique employs a liquid repair system, which is encapsulated within brittle-walled containers [5]. These containers are fractured after impact and allow the liquid resin to flow into the areas of damage where it subsequently cures.

7. CONCLUDING REMARKS

Having in mind that the document should serve as a baseline for the selection of a suitable repair technique, applicable to W/T blade non-sandwich parts, which will then be used in an experimental investigation the following three repair techniques are proposed:

(a) *Resin injection* for minor delaminated regions, matrix cracking, or dry spots

(b) *Plug/patch repair* for delaminations

(c) *Scarf repair* for delaminations

As the exact method, which will be selected for further investigation strongly depends on the available techniques used by the industrial partners in WP11, a questionnaire has been prepared in line with this document. The questionnaire will facilitate in the description of each repair method details, such as dimensions of damages that can be repaired, curing cycling of the patch repairs, etc.

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