TCO F Module – Describe Composite Laminate Fabrication and Bonded Repair Methods

F1: Understand the basics of composite laminate fabrication

The simplistic view of structural composite fabrication is that fiber reinforced plastic composite components are fabricated from “wet” material, in many cases epoxy prepreg materials, and made into their finished hard form using heat and pressure. The heat and pressure are often supplied by a pressurized oven called an autoclave. That is a simple description of the process, and the actual fabrication process is quite complicated with many parameters that can affect the quality of the composite component.

The Layup Process: The basic steps of one of the most often used process (i.e. autoclaved prepreg cure) for fabricating composite parts is as follows:

Step 1 The composite prepreg material is received and, if accepted based on tests meeting the specifications, the material is stored in a freezer until needed

Step 2 A layup manufacturing plan is prepared per the part drawing

Step 3 After the material is removed from the freezer and allowed to warm to room temperature, individual plies are cut out and laid down in order on the layup tool (in many cases, the layup tool and cure tool are the same part)

Step 4 Each ply is inspected after lay-down for orientation and periphery

Step 5 In many cases, a debulk cycle is required to remove air from between the plies and better consolidate the plies. This is often performed after the complete laminate has been laid down on the cure tool. Some materials are more difficult to process, and a debulk cycle may be required for every 5 or 6 plies. The debulk cycle is performed using a reusable vacuum bag and vacuum pressure for a specified time.

Step 6 After all the plies have been successfully laid down the laminate assembly is bagged using a reusable vacuum bag

Step 7 The bagged laminate assembly is then inserted into the autoclave, vacuum and autoclave pressure is applied, and the part is cured while in-process data, such as temperature, vacuum and pressure are monitored

Step 8 At the end of the cure cycle, the part is allowed to cool down and the bag is removed

Step 9 The bond assembly is visually and NDI inspected for defects and anomalies

Step 10 The bond assembly is then edged trimmed to the desire shape

Step 11 The finished part is then assembled to the aircraft component (e.g. horizontal stabilizer main torque box skin panel)

Autoclaves vs. Ovens: Some OEMs utilize a different process for curing epoxy prepreg laminates. They prefer to use an oven instead of an autoclave, which only cures components using vacuum pressure. OEM's using ovens rather than autoclaves are somewhat limited in the scope of parts that they can produce because some materials and part configurations require the full pressure of an autoclave. Autoclaves are many times more expensive and complicated than are ovens. Both processes still require the same fabrication steps with the only difference being the addition consolidation pressure that an autoclave can provide.

Design and Processing for Low Cost: Reliable repeatable composite laminate fabrication is a process that really starts with design of the part, design and fabrication of the tooling and ends with assembly of the part to the main component or aircraft. Manufacturing processes and tooling are the elements which control the success and cost of a composite component, and as such it is essential that they be integral parts of the design process.

The basic problem facing the OEM manufacturing engineers is producing reliable composite hardware at an acceptable cost. In order to do this, understanding that the basic material costs are high compared with metal raw material forms (e.g. aluminum sheet, plate, extrusions and forgings), labor intensive steps in the process such as ply cutting and layup have been mostly eliminated for large parts through automation. As an example, during the ply-by-ply lay down process, plies for the skins of major composite components are laid down on the female layup tool by automatic tape laying machines, eliminating the human touch labor. However, after each ply has been laid down on the tool, it is inspected for orientation and periphery by an inspector, so the automatic lay-down process stops and starts up each time.

Emerging Developments in Composites Processing: There some very interesting developments in composite processing. Manufacturers are always looking for ways to eliminate cost and "touch labor," or create composite parts with difficult to manufacture shapes and performance enhancing features (e.g. through thickness reinforcements). Some of these new or relatively new composite manufacturing technologies include:

- *Tow placement:* Tow placement is another method of laying down epoxy prepreg material. With Tow Placement, the material is stored on preimpregnated spools of string-like composite tows. (A "Tow" is comprised a string of 3000-6000 individual fibers.) Multiple spools are held in a creel which aligns the Tows into parallel rows that are fed into the tow-placement machine head which then lays the material down on the cure tool or mandrel. The advantages of tow-placement are: a) the creels can contain tow material containing different fibers so that hybrid (e.g. carbon and glass) laminates can be created automatically, b) the material can be laid down on tools to create complex curved parts unlike tape-laying machines which only lay down material to create flat or gently curved parts, and c) material laydown rates can far exceed those of manual layup.

- *Thermoplastic forming:* This process utilizes thermoplastic materials which have no cross-linking during cure unlike epoxy thermoset materials. This allows for reforming if a part has been cured with anomalies. Thermoplastic materials are more difficult to layup and cure, because they often stiff and boardy feel and because they usually cure at higher temperatures (650oF to 750oF) than epoxy thermosets. The attractions for parts fabricated from thermoplastics is that they are much more resistant to environmental effects, and the prepregs can be procured as precured individual ply sheets for forming into various shapes in a heated press.

- *Resin Transfer Molding (RTM):* This is a resin injection process in which fiber preforms are impregnated with resin inside of a rigid closed mold. Resin is injected at high pressure, and the mold is heated via imbedded heaters without the need for an oven or autoclave. This process is useful if the required part has a complex shape, or if large quantities of parts are to be produced. Due to extremely high tooling costs and lead times, the RTM process is cost effective for producing large quantities of parts, or for producing parts having complex geometry.

- *Vacuum assisted Resin Transfer Molding (VaRTM):* This liquid forming process is similar to the RTM process, but uses vacuum to assist in moving the resin through the heated mold. The molds differ from RTM as well in that a traditional Layup mandrel is used in conjunction with a flexible vacuum bag rather than an expensive closed mold. Heating is done either in an oven or an autoclave. VaRTM is especially useful for curing large parts with complex shapes (e.g. plastic boat hulls).

F2 Understand the basics of composite bonded repair

Similar to the original part fabrication process, a simple view of composite bonded repair is that damaged composite components are patched with “wet” materials, sometimes prepreg materials, and the patches made into a finished hard form using heat and pressure. The purpose of bonded repairs to structural composite components is either to restore structural capability, or seal a damaged area from environmental effects.

During the original part fabrication, the OEM has the responsibility of producing reliable repeatable composite components that have the required performance, while keeping costs to a minimum. The repair shop has the responsibility of performing reliable repeatable repairs that restore structural performance, fit and form, while minimizing operator revenue losses. The repair shop must reliably restore aircraft safety and perform the repair with minimum cost and service interruption without the sophisticated tooling and fabrication equipment of the OEM. Many bonded repairs must be performed on-aircraft; therefore the bonding process must be performed without autoclave pressure. Those damaged components that can be easily removed from the aircraft can be repaired using an autoclave providing there are no size restrictions.

Prepreg and Wet Layup Repairs

- *Prepreg repairs:* These are bonded repairs using either the original part prepreg material or a substitute prepreg material. Prepreg repairs can be performed using an autoclave if the damaged part can be easily removed from the aircraft. In this case, providing the repair bonding procedure is the same as the original part fabrication procedure, the repair plies will have the same properties as the plies removed or damaged. Prepregs repairs can also be performed using just vacuum pressure and heat. Repair plies using this process, will usually not have the same properties as the original autoclaved prepreg plies. Prepregs, during original part fabrication, are subjected to autoclave pressure of between 35 to 90 psig, where volatiles are vented and porosity limited. Vacuum bag prepreg repairs may contain additional to normal porosity that can reduce compression strength and stiffness, when compared to the original autoclave cured part. This may not be the case when performing vacuum cure repairs to composite parts that were originally cured in an oven where no pressure other than that provided by vacuum is applied. The main difference between vacuum cure repairs and original parts cured in an oven is probably the control of the heating source. Heat provided in an oven is potentially more consistent throughout the laminate compared with the heat provided by a hot bonder and heat blanket during a repair. Prepreg repairs, both vacuum bag and autoclave processed on commercial transport structural composite components, are typically processed at temperatures ranging from 250^{o}F to 350^{o}F. Prepreg repairs can use either tape or fabric forms, which unfortunately have a limited shelf life. They must be kept in a freezer in specified conditions, and after their expirations dates, they must be either scrapped or re-tested for acceptance.

- ***Wet layup repairs:*** These are bonded repairs using special two part epoxy resins and dry fiber mats. The resin ingredients are kept sealed in separate containers at room temperature until mixed to requirements. These resin ingredients have long shelf lives as long as the cans remained sealed. The mats, woven similar to fabric prepreg materials, are also kept at room temperature. The mats have no expiration date so long as they are kept in reasonably dry conditions and free of contamination. Each wet layup repair ply consists of a fiber mat, cut to the specified size and laid down oriented in a specific direction, with the mixed resin brushed on until the mat is impregnated with the correct amount. This process is repeated for all subsequent plies. The lay down process is slower and potentially more variable than for prepreg, but the wet layup repair materials have more convenient and less restrictive storage requirements.

Repair Classifications: There are often three classifications of repair in approved repair documentation. As an example, the following repair classifications are typical for Boeing SRMs:

- *Permanent repairs:* Permanent repairs are repairs that restore either original part capability or sufficient capability to carry the required loads. These are considered terminating repairs meaning that, under normal circumstances, no further action is required. Prepreg repairs processed at 250^{o}F and 350^{o}F are usually permanent repairs. Wet layup repairs processed at 180^{o}f to 200^{o}F are also often classified as permanent.

- *Temporary repairs:* Temporary repairs are either performed to seal damages detected on the ramp, or are repairs that are considered not to have sufficient durability to remain on the aircraft for an indefinite length of time. Temporary repairs are usually only allowed for one or a few flights. Many temporary repairs utilize wet layup materials processed at room temperature up to 150^{o}F.

- *Time-limited repairs:* Time-limited repairs are repairs that may restore sufficient part capability, but may not have fully proved durability. These repairs may be allowed to remain on the aircraft for many flights, but have an inspection schedule with a final remove and replace with a permanent repair requirement. Many time-limited repairs utilize wet layup materials processed at 150^{o}F to 200^{o}F.

For a more detailed discussion on the classification of repairs see C1 of Module C.

Repair Categories: There are basically two categories of repair:

- *Depot level (military) or maintenance base (commercial):* These repairs are performed at a major maintenance base in a controlled environment. Repairs in this environment can range from simple on-aircraft wet layup vacuum bag repairs to larger, more complex autoclave prepreg repairs to critical areas of removable components. In either case, repairs performed at the depot or maintenance base are typically permanent repairs.

- *Field level (military) or line station (commercial):* These repairs are performed at a forward operating base with limited facilities. Repairs in the field are usually limited to small wet layup vacuum bag bonded repairs and bolted overly repairs. Due to the limited facilities and time, most field or line repairs are temporary or time-limited.

F3 Describe the detailed processing steps necessary for laminate fabrication (factory), bonded repair (maintenance base or line station), and Material Review Board (OEM)

Laminate Fabrication

Section F1 presented the basic steps required for composite fabrication from ply layup to assembly of the part into the main aircraft component. To demonstrate more completely the steps in the bonding process of composite laminates in the factory, the following is presented as an example of an autoclave cured skin panel bond assembly at a major OEM:

Step 1 Composite material is received and accepted based on tests meeting the specifications

Step 2 A layup manufacturing plan is prepared per the part drawing

Step 3 The female layup and cure tool is cleaned and it’s surface prepared with a release agent so that the first ply laid down does not stick to the tool during cure

Step 4 Material is removed from the freezer and prepared for use

Step 5 Each ply is laid down on the layup tool by tape laying machine programmed to the manufacturing plan, each ply manually inspected for orientation, periphery and correct order per the manufacturing plan[1]

Step 6 The laminate is vacuum bagged and debulked to eliminate air trapped between plies during lay down, and to prevent potential wrinkling. In some cases the debulk cycle is preformed every 6 plies or so, in others the double vacuum debulk (DVD) cycle is used to removed entrapped air and potential wrinkles from the total laminate in one operation

Step 7 The debulk bag is removed

Step 8 Precured stringers are located in positions on the debulked skin with film adhesive[2]

Step 9 The whole skin assembly is vacuum bagged for cure, with appropriate stringer tooling, breather and bleeder plies, edge dams and bag sealant.

Step 10 The vacuum bagged part is installed in the autoclave and the cure process is programmed

Step 11 The cure is started and in-process data such as temperature, autoclave pressure and vacuum are monitored and recorded on strip charts

Step 12 The recorded process data record is inspected periodically for conformity to the cure plan

Step 13 The cure cycle ends and the part is allowed to cool down

Step 14 The vacuum bag, bleeder and breather plies are removed, and the part is visually inspected for defects

Step 15 The part is subjected to TTU inspection and the results of the scan recorded

Step 16 Inspectors examine the printed scan results and record any detected anomalies for Material Review Board (MRB) action

Step 17 The part is then edge trimmed to the final assembly periphery by water jet cutters and the correct geometry is verified for accuracy by an inspector

<Note 1>In some cases, as the experience and confidence bases increase, the ply-by-ply inspection after lay down and cutting may be changed to a ply sampling plan. This will significantly decrease the manufacturing time cycle for each part.

<Note 2> The precured stringers have been previously laid up and cured in a separate process. Other OEMs may precure the skin and then bond the uncured stringers to the skin in another cure cycle. Either way, these processes are termed “co-bonding.” The classic method of fabricating a stiffened skin panel is to cure both skin and stringers together, and is termed “co-curing.” In many cases, when assembling uncured stringers to relatively thick parts, during the “co-cure” process, the stringers sink into the skin due the presence of heavy stringer tooling bearing down on the skin during the cure cycle. That is one of the reasons that some OEMs have turned to the “co-bonding” process. In this process the stringers do not need heavy tooling (or mandrels) to ensure the correct shape for the stringers. There is a critical issue with the co-bonding process. That is the issue of surface preparation of the pre-cured part. In order to provide for a good bondline, the precured part mating surface will need to be prepared so that a) it does not have a smooth surface, and b) it may need to cleaned to ensure all potential contaminates are removed. Some OEMs cure a “peel ply” to the pre-cured part mating surface during it’s cure cycle. This ‘peel ply” is removed immediately prior to the assembly of the pre-cured part to the uncured part, and helps to provide for a slightly roughened (i.e. the imprint of the peel ply fabric) and uncontaminated surface for bonding.

As can be seen, there are many steps in the bond assembly process, and many places for errors. It is essential that errors be kept to a minimum and any anomalies that do result are detected. The automatic equipment helps to reduce human errors; and the in-process quality controls and inspections, and post fabrication inspections are provided to ensure that errors are detected.

After the above process, the part is primed, assembled to the main aircraft component, a surface protection system applied (aluminum flame spray or aluminum mesh) and enamel painted.

Bonded Repair

A typical on-aircraft hot bonded repair includes a number of the basic steps that are similar to the original component fabrication process (material preparation , layup, vacuum bagging, cure, and inspection). Repair material control and handling are also similar to the original material control at the OEM. One difference may be that some repair shops do not perform material acceptance tests. These shops typically use only small quantities of material on an infrequent basis, so they often procure materials from third party suppliers who perform all receiving inspection.

The actual steps that are necessary to perform a permanent hot bonded repair are the following:

Step 1	Damage assessment and mapping
Step 2	Damage removal
Step 3	Drying (moisture or fluid removal)
Step 4	Scarfing out the damaged area
Step 5	Surface and repair area preparation
Step 6	Repair material preparation
Step 7	Layup of the repair plies
Step 8	Installation of the vacuum bag and thermocouples
Step 9	Cure cycle and in-process cure data monitoring (i.e. temperature and vacuum)
Step 10	Post-repair inspection
Step 11	Surface protection system restoration

As mentioned in F1, a quality permanent hot bonded repair to a sandwich part currently takes at least 14 hours from damage discovery to paint restoration. If damage is found in a solid laminate, the Boeing SRM procedure to completely dry the damaged area takes 24 hours, so to complete a permanent repair under these circumstances can take over 30 hours. Temporary and time-limited bonded repairs may take less time, depending upon the cure temperature, however any moisture present should be eliminated.

Material Review Board

All OEMs have a factory process called the Material Review Board (MRB). It is a process that is intended to make dispositions concerning reported defects or unsatisfactory raw material, and take corrective actions as necessary. Dispositions may include repair or rework, scrapping the part or material, or using the part or material as is. Corrective action may be taken to reduce the number of repetitive errors or defects in the fabrication process.

The following is a description of one OEM's Material Review Board procedure:

“The MRB documents the "instant" problem and gathers quality data. The corrective action process analyses the quality data and determines causes, trends and long term solutions.

Both the Material Review Chief and Corrective Action Chief report to the Manager of Product Assurance Engineering and have separate organizations to carry out their functions.

The material review process starts with an inspection report (rejection notice) provided by one of many inspectors. The rejection is reviewed and entered into the Quality Management System (QMS) database. The rejected material or part is reviewed to determine its disposition. It may be used as is, scrapped, reworked, or, if raw material, returned to the vendor.

The purpose of the corrective action process is to prevent or reduce the rate or recurrence of a defect, discrepancy, failure, or other condition judged significantly detrimental to safety, cost, quality, or performance of the product by correcting the root cause. The process is initiated by management request, document review, QMS thresholds, or analysis reports. Problems are investigated to determine the root cause and appropriate corrective action.

Problems that cannot be resolved at a lower level are resolved by Corrective Action Committees. These committees are composed of mid-level management personnel that address problems that cross departmental lines, problems unresolved by departmental corrective action activities, root causes of repetitive problems, high dollar and high frequency problems. Follow-up is assigned to ensure corrective action is effective.

It can be seen from the above, the Material Review Board is a process to provide for reliability of the product in service by making dispositions of reported defects and to prevent additional manufacturing cost by corrective actions.”

F4 Describe key characteristics and processing parameters for laminate fabrication

Good repeatable composite laminate fabrication is dependant on a number of key characteristics and parameters. The following are important for good quality autoclaved cure composite parts using prepreg material.

Prepreg material: Fresh prepreg material is essential for consistent and high quality cured laminates. Prepreg materials have a limited freezer storage lives (often less than six months), as well as limited allowable out-time (often less than ten days) when the material has been removed from the freezer but before it has been cured. If the material exceeds its storage life or its out-time, the matrix intermolecular cross-linking may not fully occur during cure, yielding a cured component that won’t meet strength requirements. Porosity and delaminations are often the result of using old material. Old material may feel “boardy” to the touch, and can be difficult to manipulate during hand layup, automated layup, ply consolidation and automated forming operations. The material must also be kept free of debris and fluids during processing to prevent strength degradation through contamination.

Tooling: Cure tools must be designed correctly and fabricated from materials with matching coefficients of thermal expansion with the composite material in order to produce laminates that won’t warp during the cure cycle. Mandrels for drape-forming stiffeners, spars and ribs must be designed with slightly open angles so that they can be easily removed after cure. They also must be designed so that the material can be draped around them reasonably easily for reasons given above.

Ply layup: Most OEMs use some method of automatic ply lay down in order to speed up the process, and eliminate human errors. Tape material can easily be laid down by machines, whereas fabric is more difficult, and in a majority of cases is laid down by hand. An important aspect of ply layup is inspection by a qualified inspector to ensure that the plies have been laid down in the correct orientation and order.

Debulking: Many composite materials will require debulking every 5 or 6 plies to remove any air that has been trapped between plies during lay down. Air trapped within a laminate can cause wrinkles and porosity during cure. The debulking procedure is typically performed under vacuum and for some materials may for some require heating. A method called double vacuum debulk (DVD) has been developed to obviate the need for a debulk cycle every 6 plies. DVD has been used to successfully remove entrapped air from laminates of more than 40 plies prior to the cure cycle.

Bagging system: OEMs typically have developed reusable vacuum bagging systems for autoclave curing of composite laminates that provide the means of removing trapped air and escaping volatiles (through venting) and encouraging consistent rein flow throughout the laminate. The bag must be vacuum tight to ensure proper ply consolidation during cure. Typical autoclave pressures range from 36-45 psig for sandwich parts to more than 75 psig for laminate stiffened parts in order to ensure a well consolidated part without porosity.

Cure monitoring systems: During cure, a monitoring system is required to review all processing parameters throughout the cure cycle to ensure a good quality part which meets the desired structural performance and environmental durability. Thermocouples placed at critical locations within the vacuum bag, are monitored to ensure correct cure temperature. Autoclave pressure and vacuum are also monitored to ensure that there are no critical variations in the cure cycle that may lead to anomalies in the cured laminate.

Post-process inspection: Inspection of the cured part is an essential ingredient of the fabrication process. Both visual and NDI methods of inspection are used by the OEM to ensure that any defects in the cured parts are detected. A cured part is visually inspected after cool down and removal of the vacuum bag. It is then typically subjected to a rigorous ultrasonic inspection. Many OEMs utilize through-transmission (TTU) ultrasonic equipment in the factory for post-fabrication inspection. The medium is achieved with water jets for large components, or immersion in a tank of water for smaller parts. Very large, thick parts can be inspected rapidly with TTU, and defects as small as 0.5 inch diameter can be discovered in flat or gently curved parts. TTU equipment has limitations for inspecting parts with tight bend radii (e.g. corners on T- and I-section components). In these cases Pulse Echo (P/E) ultrasonic equipment with a small hand-held head for the transducer is used to detect anomalies within these bend radii.

F5 Identify typical processing defects which occur in composite laminate fabrication and bonded repair

Processing defects that occur during original part fabrication: Processing anomalies such as voids, delaminations and porosity typically occur during the cure process, and may be the result of poor tooling, insufficient ply consolidation, low autoclave pressure, loss of vacuum during the cure cycle, and post-cure process damages such as edge damage, dents, delaminations and poorly drilled holes.

- *Poorly designed or installed cure tooling:* Layup mandrels must be designed to produce components that match the designed part contour. If the tooling produces components that exceed contour allowables, then the components will require excessive preloading during assembly which will compromise the component ability to carry required loads. Likewise, mandrels for cocuring (e.g. stringer or stiffener mandrels) must be designed and installed with minimal mismatches to ensure proper consolidation of the cocured component. Co-bonded components must have accurate locating tooling to place the component into the position where it correctly matches the contour of its mating component.

- *Insufficient Ply consolidation:* some of the latest, tougher materials require ply consolidation prior to the cure cycle. This is due in part to the matrix viscosity, and depending on the number of plies in a layup, several compaction cycles may be necessary. In these cases, insufficient ply consolidation or compaction prior to cure can lead to voids, porosity and delaminations. The DVD debulk method is widely used to eliminate entrapped air from repair layups prior to cure by the US Navy on repairs to F/A-18 and AV8B aircraft composite parts.

- *Loss of vacuum, autoclave pressure or low temperature:* During the cure cycle, any loss of vacuum, autoclave pressure or temperature can result in anomalies such as voids and porosity. An improperly cured part may also have lower than required thermal stability in addition to lower mechanical properties.

- *Inclusions:* These can occur when insufficient care is taken during ply layup. Foreign objects have been discovered post-cure inspection such as backing paper, release film and even personal items. Inclusions are physical defects that reduce the load carrying capacity of a part. Inclusions are often attributed to a lack of diligence by the layup technicians or to lack of attention by the in-process inspectors. Post-fabrication NDI methods employed by the OEMs will discover the majority of inclusion anomalies.

- *Edge damages, dents, delaminations and fastener hole damage:* Defects such as edge damages, dents, delaminations and fastener hole damage can result after cure, during part handling, machining and assembly. Composite parts are more vulnerable to impacts than metal parts, and care must be taken during handling. Incorrect machining and drilling parameters, such as feed rates and drill speeds can lead to delaminations in and around holes and part edges.

Processing defects that occur during bonded repairs: Repair process mistakes such as the following are almost certain to lead to repairs that may have less than required structural properties, or may become disbonded in service:

- *Incorrect surface preparation:* It is essential that the protective coating (e.g. conductive coating if present, paint enamel and primer) is removed using a prescribed method such as abrading or sanding. The coatings should be completely removed over an area that will more than encompass the repair. (Note: Extreme care must be taken to avoid damaging plies when removing paint and primer.)

- *Insufficient moisture or fluid removal and drying:* All fluids must be removed from the component using vacuum and heat. Failure to remove all moisture and fluids from the repair region of the component may cause a patch bondline failure. Residual moisture or fluids can seep into the patch bondline during the cure heating cycle, destroying the chemistry of the resin matrix, or the moisture can vaporize under the elevated cure temperatures to blow the patch off the component.

- *Insufficiently cleaned repair surface:* If the abraded surface and tapered area is not cleaned sufficiently with an approved solvent, contaminates (e.g. dust) may be present in the repair bondline.

- ***Old prepreg and adhesive materials:*** Prepregs and adhesives that have exceeded their allowable out-time or are old and have expired must not be used

- ***Wet layup repair resin ingredients that have been incorrectly mixed:*** It is essential that the correct measured amounts of the two parts of the resin be mixed correctly otherwise the repair may never reach the desired state of cure.

- ***Poor vacuum bagging procedure leading to leaks during the cure cycle:*** If there are any leaks in the vacuum bag, they can be detected by good in-process monitoring of the heating unit read-outs, otherwise the repaired patch and bondline may contain voids, excessive porosity and delaminations.

- ***Incorrect in-process control:*** If the cure process is not monitored closely, wide variations in thermocouple readings, incorrect heat-up rates and cure temperature, and loss of vacuum may result. If there is a lower, or higher than, acceptable thermocouple reading, then an unevenly cured repair may result. Substructure heat sinks can affect repair thermocouple readings, and it is important to be cognizant of the substructure and thermocouples must be placed accordingly. The ramifications of vacuum loss are stated above; and incorrect heat-up rates and/or lower than acceptable cure temperatures may produce a repair with insufficient temperature or moisture resistance. If the cure temperature is too high, then the repair resin may be burned.