

# TCO I Module – Describe Composite Laminate Bolted Assembly and Repair Methods, and Perform and Inspect a Bolted Composite Repair

## I1: Describe the basics of composite bolted structural assembly. Show the differences between composites and metal bolted assembly

**The basics of composite bolted structural assembly:** The use of bonded composite parts in aircraft structures enables the elimination of thousands of mechanical fasteners that exist in similar metal components. An example would be the attachment of stiffeners or stringers to wing and fuselage skins which, in a metal airframe, employ many thousands of rivets. However, mechanical joints are still used for joining more highly loaded composite elements and components. Examples of more highly loaded joints are wing and stabilizer skins-to-spars and skins-to-ribs, component to component (e.g. wing-to-side-of-body fittings and terminal fittings) and for the attachment of fittings to such components as elevators and ailerons. This use of fasteners in critical composite joints is due to the higher joint reliability of discrete fasteners, the improved inspection capability, and the need for possible disassembly.

The capacity of a composite mechanical joint is typically designed so that the structures being joined fail before the actual joint itself. Another way to say this is that the joint is designed to be more capable of transferring the maximum load capabilities of the parts being joined. This is common of mechanical fastened joint design, and is a good rule regardless of the materials of the components being joined.

It is important to understand the effect that holes and loaded fasteners can have on the strength of the composite laminates being joined. An open hole in a composite laminate produces stress concentrations that can significantly increase the stresses at the edges of the hole compared to the stresses in the un-notched section of the laminate. The bearing stress of the fastener transferring load from one part to the other must be added to the stresses at the edge of the hole. All of these stresses cause significant reductions in strength of the laminate in the joint area.

**Composite vs. Metal Bolted Assembly:** The use of mechanical fasteners to assemble airframe structural components or elements is a mature technology. Composite part joining is no exception to this. Failure modes for composite fastened joints are similar to those for metallic fastened joints.

In spite of their similarities, the behavior of composite fastened joints differs significantly from that of metallic fastened joints, and they deserve special attention because of several reasons:

- a) *Composite Notch Sensitivity reduces Hole Bearing Strength:* The notch sensitivity of composite materials, which result in significant reductions in the strength

due the presence of a hole (e.g. approximately 50-60% from a similar laminate without a hole).

b) *Composites have reduced Z-directional strength:* Composite fastened joint strengths are a function of the actual laminate, i.e. ply stacking sequence, percentages of plies in each direction (e.g. 0, +45, -45 and 90 degrees to the loading direction), fiber volume, etc. Composite laminates consist of anisotropic layers (plies) and the laminate layups can change this anisotropy toward isotropy. A layup of 25% 0o, 25% +45o, 25% 90o, and 25% -45o plies yield a “quasi-isotropic” laminate which almost equates to a metal isotropic part. This kind of laminate layup is probably the best type for composite fastened joints. It has the same percentage of fibers in all of the standardized directions, thus allowing for a load in any direction to have good load paths around the hole and at the same time having a good bearing strength to unload the fastener. The resultant laminate is called “quasi-isotropic” because it has the same properties in two directions only (i.e. longitudinal and transverse). It still has very little tensile strength in the “zee” (through thickness) direction. A metal such as aluminum has similar properties in all three directions, although some aluminum alloys have poor through thickness tensile strength.

c) *Composites are more susceptible to Fastener Bending:* Fastener bending can have a more significant effect on the joint strength on a composite fastened joint than for a metallic fastened joint. This is due to the fastener flexibility exerting higher bearing stresses on the outside plies of the laminate contributing to earlier failures than would be the case if there is no bending and the fastener bears uniformly through the thickness of the laminate. Bolt bending in fastened metal parts is not a good thing either, and excessive bolt bending can lead to lessened strength in the joint. However the increased local bearing stresses due to bolt bending in a composite joint can lead to delaminations caused by microbuckling of the fibers, and crushing of the outside plies.

d) *Composites are more sensitive to Fastener Clearance:* Efficient load transfer from fasteners to the parts being joined can have a large effect on the joint capability. For a given configuration, the fastener fit in the holes is important to this efficiency. If fasteners have a close tolerance fit in the holes, they not only transfer load efficiently but can also prevent hole wear. Critical joints in metal structures usually employ close tolerance, transition-fit and in many cases (e.g. riveted joints) actual interference-fit holes. When bolts are inserted into close tolerance or transition fit holes in relatively thick metal parts, they quite often have to be firmly tapped in with a hammer. This cannot be the case for composite fastened joints. Any kind of very close tolerance or transition-fit fasteners will cause damage to the holes in the composite laminate parts when installing the fasteners. Lack of fit can have a serious effect on the efficiency of composite fastened joints. This need to have some clearance in the holes for composite fastened joints called for significant research to optimize composite drilling, hole fit and hole and fastener tolerances. The results of this research led to the use of a holes and fastener sizes and tolerances that effectively result in a fit that is between close tolerance and what is called Class 1. This type of fastener fit has proved to be effective in providing good load sharing in multiple fastener joints.

e) *Fastener Clamp-up issues when assembling composite parts:* Care must be taken when mechanically assembling composite components. Using the fastener clamp-up to

close gaps between parts can lead to delaminations. Metal parts can bend to accommodate moderate gaps, whereas composite laminates tend to delaminate if subjected to local abrupt changes in curvature. It is essential to use some form of shimming if part tolerances or warpage cause fit-up problems. There have been several lessons learned in this area leading to the re-design of composite tooling, shimming techniques suitable for composite assembly and reductions in material thickness variations so that gaps are either eliminated or significantly reduced.

## **I2: Describe the basics of composite bolted repair. Show the differences between drilling and cutting composites and metals**

*Bolted Composite Repair Basics:* Bolted or bonded repairs are made to damaged composite parts to restore component strength and stiffness properties so that the maximum design loads can be carried by the component. Typically the ideal bolted repair will follow the same design guidelines as the original manufactured component such that failure of the repaired part does not occur in the bolted repair area. To this end the selection of the repair doubler, fasteners, number of fasteners, fastener pattern and spacing must be carefully considered. The main consideration for repair of any aircraft component is that in general, aircraft components such as wing, stabilizer and fuselage skins are loaded in multiple directions. A bonded repair, if performed correctly (i.e. a sufficient number of repair plies and a good bond), has the advantage of being able to restore the component mechanical properties in all directions, without the need to understand the component design loads. To ensure this for a bolted repair, the repair has to be carefully designed and knowledge of the component design loads is essential. Drilling holes in a component that may be loaded in multiple directions can have significant effects on the capability of that component. Add the bearing stresses of fasteners and the stress concentrations caused by the holes and the increased state of stresses at the fastener holes can be higher than the component was designed for. Because most repair technicians do not have knowledge of the component design loads, when repairing a damaged component with a bolted repair, it is essential to follow the repair instructions contained by the source documentation.

Bolted repairs to damaged composite structures are enacted frequently. One reason for a bolted repair is to temporary repair if the time or facilities to perform a permanent bonded repair are limited. Due to the increased use of composite material in critical components on military and large commercial aircraft, permanent bolted repairs are being used to repair damage to thicker composite laminates that comprise highly loaded components such as wing or stabilizer skins and spars.

Bolted repairs are often used for the repair of composite parts when the thickness of the part being repaired requires a very large scarfed out area. This is due to the very shallow taper ratios in current use for bonded repairs. Typically for bonded repairs to solid laminates a taper ratio of 30:1 is used. As an example of this scarf taper ration, if 15 plies are damaged producing a damaged area of 1.0 inch diameter and have to be removed, the resulting scarfed out area ends up being almost 9.0 inches diameter. This is now an effective damage of 9.0 inches in diameter, whereas using a bolted repair doubler the original 1.0 inch diameter damage is cleaned out and the bolt holes are drilled in the composite part at a diameter of 2.25 to 2.50 inches. Basically

**Comment [JLE1]:**

This may be untrue. Many bolted repairs have up to three rows of fasteners at 4D spacing surrounding the damaged area.

considerably less of the original laminate has been removed. For structures such as fuselage, wing or stabilizer skins employing laminates stiffened with stringers at close spacing, bonded repairs can become complicated.

*Drilling Differences between Composites and Metals:* There are significant differences in drill types, lubrication, speed and feed rates for drilling metal versus composite parts. The drilling of metal parts is typically performed using steel drill bits, a relatively slow drill speed and a lubricant. As an example, the speed for drilling metal parts (e.g. titanium) is usually in the order of 450 rpm for drilling a 0.25 inch diameter hole with the drill bit lubricated with Boelube or a similar lubricant such as cetyl alcohol. Drilling composite parts on the other hand requires a totally different approach. Fiber breakout and/or delaminations can occur during drilling of carbon parts if proper procedures are not followed. Drill bits for Composites are usually solid carbide or diamond tipped, and drill speeds need to be much higher. Using the same example, for drilling a 0.25 inch diameter hole in a CFRP part, drill speed needs to be 5000 rpm and drilling is often performed without a lubricant. Basically in order to eliminate defective holes (delaminations and fiber breakout) high drill speed and a slow, controlled feed rate are used. Fiber breakout of the last ply to be penetrated by the drill bit can be avoided by using a block of wood as a backup for the drilling operation.

The need for the carbide drill bit is that steel drill bits wear out very quickly when drilling carbon and glass fiber materials which are very abrasive. There are several reasons for the higher drill speed, one of which is the need to eliminate splintering of the edges of the hole. Another reason for the higher speed is so that pressure can be reduced, and low feed rates can be used. Excessive pressure (i.e. high feed rates) during the drilling operation can cause delaminations and fiber breakout.

Carbon composite parts fabricated from unidirectional tape are very difficult to drill without fiber breakout. Typical production parts that are constructed with tape or tows (see fiber placement as described in Module J) will employ fabric for the surface plies in order to eliminate or greatly reduce fiber breakout when drilling.

It is highly recommended to refer to the drilling procedure section of the source documentation (e.g. SRM) before performing a drilling operation in composite materials.

*Cutting and Machining differences between Composites and Metals:* Cutting and machining composite parts requires some different processes and equipment than those applied to metals. When performing composite repairs, surfaces are often prepared with sanders and grinders. Metal repairs are often repaired with routers and various metal working tools. Sanders and grinders are high speed hand tools used for light sanding, feather edging and cutting of tapered and stepped scarfs for bonded repairs. A high skill level is required when using these tools because of their high speeds (e.g. 18,000 rpm or faster).

Composite materials behave differently than metals during machining. Parts made with Aramid fibers for example require special machining and cutting techniques because the Aramid fiber machining characteristics are poor. Aramid fibers tend to fuzz when cut, this can also happen when cutting or machining Aramid honeycomb core. Special efforts are made to keep

machining and drilling temperatures down when working on composite parts. Machining temperatures should be kept below the glass transition temperature (T<sub>g</sub>) of the material being worked on. The T<sub>g</sub> of an epoxy material is the temperature at which the material transitions from an elastic state to a viscoelastic state. Typically this means keeping the temperature at the cut edge below 150°F or so to ensure clean cutting. Drilling or cutting at temperatures above the material T<sub>g</sub> may cause clogging. High temperatures at the cut edges are caused by high speeds and pressures. The high speeds used for machining or drilling composites requires that pressure be kept low by significantly reducing the feed rate below that typically used for machining or drilling metals. It is important to follow drilling instructions contained by source documentation, because they typically detail feeds and speeds for drilling composite parts that will ensure temperatures at the cutting edge that will be below the material T<sub>g</sub>.

When machining, cutting or drilling of metals, the debris that is removed from the material come away in the form of shavings or chips. These metal shavings are often carried away by the lubricant or forced air which is typically used when machining, cutting or drilling metals. This does not happen when performing the same operations on parts made of composite materials. Due to the higher cutting and machining speeds used, the cut material comes away in the form of a fine dust. To prevent the repair technicians ingesting this dust, approved vacuum equipment must be used with all composite cutting, grinding, or drilling tools. Pneumatic tools with rear exhausts are recommended as air is directed away from the work and dust is not blown around the shop, and vacuum attachments to the tools can be used to provide dust extraction.

### 13: Demonstrate composite drilling versus metal drilling

The instructor will demonstrate drilling operations for a) titanium sheet, and b) a carbon composite laminate. He will show the differences needed in drill speeds and feeds required to successfully drill holes in the CFRP laminate.

*Titanium sheet drilling operation:* Mark the fastener pattern on the titanium sheet, then place the sheet in a fixture and using a #30 ST10-907-J2 steel drill bit, drill (using 750 rpm) the fastener holes in the doubler, using Boelube to lubricate the drill bit. When all the fastener holes have been drilled, remove all burrs from the holes.

**Comment [JLE2]:**  
Must ream or drill the hole to full size.  
I'm guessing 0.25" dia?

*Carbon Laminate Contrast of Feeds and Speeds:* Mark the fastener pattern on the composite laminate, then place the laminate in a fixture. Using the same drill bit (i.e. #30 ST10-907-J2 steel drill bit) and the same drill speed (750 rpm) as used for drilling the titanium sheet, drill two fastener holes in the composite laminate. (A dust capturing vacuum will be used during all drilling operations.) Feed the drill at a much slower rate than for the first two holes drilled. Next, replace the drill bit with a #30 ST1257B solid carbide drill bit, and drill the next two holes using 5000 rpm drill speed and a wooden backup.

**Comment [JLE3]:**  
Must ream or drill the hole to full size.  
I'm guessing 0.25" dia?

*Compare Hole Quality:* Now remove the composite laminate from the fixture and examine the holes. (A boroscope may be used to further evaluate hole quality.) The second pair of holes drilled will be of a superior quality than the first pair of holes drilled. The first pair of holes drilled may exhibit fiber breakout on the drill entry side, and will most certainly exhibit fiber

breakout and possible splintering on the drill exit side. In addition, the first pair of holes drilled may exhibit delaminations within the holes. The second pair of holes drilled in the composite laminate with the carbide drill bit, increased drill speed, decreased feed rate and wooden backup should compare favorably with the holes drilled in the titanium sheet using the steel drill bit and lower drill speed.

#### **I4: Describe process parameters which affect bolted composite repair quality and in-process controls necessary to avoid defects**

**Critical Processing Parameters:** There are a number of critical processing parameters which can affect bolted composite repair quality:

- a) *Surface preparation:* It is essential that the surfaces are clean and there is no protruding damage (e.g. fibers) that may prevent the doubler and base composite part from mating properly. If a repair doubler is sitting up and not in contact with the part being repaired, fastener installation may be affected, e.g. effectively changing the fastener grip length (see item c below)
- b) *Properly drilled holes.* Good, consistent fastener fit is essential for good load sharing in a repair fastener pattern. If the holes have been drilled with varying tolerances or at off-angles, the fasteners will not all fit in the same manner, and some fasteners will unload before others, increasing the bearing stresses in those fastener holes. In extreme cases, holes with variable fits can lead to failure of the bolted repair
- c) *Fasteners with the correct grip lengths:* If a fastener has insufficient grip length (the part of the fastener without threads), concentrated bearing stresses on the fastener shank may result. Also any threaded portion of the fastener which bears on the laminates being joined may cause damage inside the holes, as well as creating the potential for incorrectly clamped sleeves. Incorrect grip length fasteners have contributed to bolted repair failures, regardless of the materials being repaired.
- d) *Correctly installed fasteners.* Fasteners must be installed per applicable specifications with proper clearance, sealant, sizing, and clamp-up. If the fastener is incorrectly installed, i.e. with insufficient clamp or unsatisfactory sleeve formation, the designed repair strength may not be attained. In some cases where the back face of the part being repaired is not easily viewed, it is very important to perform the fastener installation correctly using the specified blind lockbolt installation tool.
- e) *Properly applied sealant:* If the sealant between the repair parts and the edge seal has not been applied correctly, moisture paths may result which can lead to fastener corrosion and freeze-thaw damage and laminate moisture absorption through the damage area.
- f) *Improper fit-up requiring excessive clamp-up:* Due to poor tolerance control, warpage and other geometric variations gapping can occur when using bolted repairs to

damaged composite components. It is essential to make sure that the repair plates have the same contours as the composite parts being repaired. If moderate gapping still remains after repair plate forming, then laminated peelable shims are recommended.

**In-process controls necessary to avoid defects.** All repair is intensely depended on technician workmanship, and their ability to comply with work instructions and applicable specifications while performing the repair. As such, it is advantageous to have two technicians (or a technician and an inspector) involved in the repair process so that one technician performs the repair step, while the other technician or inspector checks to see if the step has been performed correctly. An example of teamwork to ensure a good bolted repair is as follows:

Technician #1 collects all necessary equipment and repair parts; technician #2 checks to see that all equipment is appropriate and the correct repair parts have been gathered

Technician #1 prepares the surface, removes any protruding damage and cleans the surfaces; technician #2 checks to see that the surface preparation has been performed adequately

Technician #1 cuts the repair doubler to shape; technician #2 inspects the final shape. He then places the repair plate on the damaged area to see if any gaps may be present between the repair plate and the damaged part. If gapping is present, technician #1 reforms the titanium repair plate to better fit the damaged area.

Technician, using a fastener pattern template, drills and reams holes in doubler and composite part; technician #2 inspects holes in both parts in the order of hole enlargement and final reaming

Technician #1 applies fay surface sealant to the mating surfaces of both the repair doubler and the damaged composite part; technician #2 checks the application

Technician #1 installs the fasteners; technician #2 inspects for correct installation

Technician #1 applies the edge seal around the repair doubler; technician #2 inspects it.

All composite repairs must be conducted to work instructions that include steps that document successful inspection at the completion all significant process. A second person must be used to perform inspection activities, who is responsible for verifying the correctness of the process step, and for signifying on the work instructions that he has verified the process step. This system of checks and balances creates a reliable method to ensure that the repair process has been enacted correctly.

**I5 [LAB #5]: Demonstrate and apply common damage removal, surface preparation, drilling and fastening techniques used for bolted composite repairs and how to inspect them for acceptability**

**Note: this Laboratory exercise is meant to serve as an example for how the indicated composite repair principles can be taught. Individual Trainers may choose different methods to convey the same underlying principles.**

Laboratory #5 Instructions: Students will participate in the bolted repair of damaged laminate panels in a controlled laboratory environment using titanium repair plates and fasteners, and inspect the repairs for acceptability

**Laboratory #5 equipment list:**

Nine damaged eight ply carbon laminate panels (15 inch by 15 inch)  
Titanium Doubler, pre-cut and pre-piloted (.063 Ti-6Al-4V annealed sheet)  
XX dozen protruding head blind bolts (Monogram 98524-8 or Fairchild 5M902-8)  
4 Blind bolt installation tools  
YY temporary fasteners (CBX-BF (Bigfoot))  
4 cylindrical temporary fastener installation tools  
Boelube or cetyl alcohol for 4 drilling work stations  
4 Drill motors  
#30 ST1257B carbide drill bits  
#10 ST10-937-B steel drill bits  
#10 ST1257B carbine drill bits  
.02600 inch ST 186 4R carbide reamer  
4 Drill fixtures  
Solvent cleaner

The instructor will demonstrate the damage preparation, doubler and composite Drilling operations, and fastener installation procedure, and then the students will drill bit be paired off for each pair to perform a bolted repair.

The bolted repair procedure is as follows:

- Step 1 The damage is to be cleaned up i.e. any damaged materials are to be removed. Any loose or broken fibers are to be removed.
- Step 2 Ensure that the damaged area and adjacent surface of the part are smooth and flat for the repair doubler.
- Step 3 Clean the area with an approved solvent
- Step 4 Seal the damage as applicable (i.e. if called for in the source documentation)
- Step 5 Retrieve a precut, #30 piloted titanium repair doubler with a surface finish of 125 micro inches Ra or better. Debur all cut edges corners and holes to remove all sharp edges.
- Step 6 Clamp the doubler onto the composite part to ensure that it does not move. Pilot drill all fasteners holes (#30 @5000 rpm) in the repair component, using wooden backup. Use a slow feed rate to drill the holes in the composite laminate. Use a star-pattern drilling sequence to avoid doubler creep due to thermal expansion. Install a temporary fastener in each hole after drilling to ensure doubler and part do not move.
- Step 7 Remove the doubler and place in a fixture. Drill out all piloted holes (#10 ST10-937-B steel drill bit @ 550 rpm) using Boelube as drill lubricant. Remove all burrs.
- Step 8 Reclamp the doubler onto the composite part aligning the fastener holes. Drill all holes in a star pattern using the doubler as a guide (#10 ST1257B carbine drill bit @ 4500 rpm) using a slow drill feed rate and a backing block to prevent fiber breakout. Install a temporary fastener in every other hole to ensure that the doubler does not move during drilling.
- Step 9 Hand ream all holes to full size (0.2605-0.2630 inch diameter) at reamer speed of 150-300 rpm. Install temporary fasteners to ensure that the doubler does not move during reaming.
- Step 10 Remove the doubler and debur all the holes on both doubler and composite part and debur all holes. Chamfer edge of all holes on the fastener entrance side of the doubler to the same diameter as the radius on the underside of the fastener heads.
- Step 11 Use solvent to remove any residual Boelube from the titanium repair places and carbon panel and reamed holes
- Step 12 Apply one coat of sealant to the mating surface of the doubler and composite part.
- Step 13 Place the doubler over the composite part, aligning the holes in each part. Install temporary fasteners in each corner of the fastener pattern, and then install temporary fasteners in every other hole so that opposite holes are clamped on each side of the symmetry line.

- Step 14 Select appropriate fasteners of the correct diameter and grip lengths.
- Step 15 Install fasteners in the open holes through the squeezed out sealant.
- Step 16 Remove all of the temporary fasteners and install the permanent fasteners in the open holes through the squeezed out sealant.
- Step 17 Apply a fillet seal around the repair doubler.

**I6 [LAB #6]: Verify correct fastener selection, inspect drilled holes, and check if fasteners were properly installed during bolted composite repair laboratory trials**

**Note: this Laboratory exercise is meant to serve as an example for how the indicated composite repair principles can be taught. Individual Trainers may choose different methods to convey the same underlying principles.**

- Step 1 Inspect the repair doubler for correct material, thickness, dimensions, flatness and finish
- Step 2 Inspect damage area to check for any protruding damage
- Step 3 Inspect the marked fastener edge distances and spacing on the repair doubler prior to drilling holes
- Step 4 Inspect all fastener holes in doubler and composite panel for correct size and condition. Perform this inspection for each increment of the drilling procedure.
- Step 5 Inspect repair doubler and composite laminate for cleanliness after solvent clean
- Step 6 Inspect the selected fasteners to see that they are the correct size and grip length
- Step 7 Inspect faying surface sealant application to make sure that the sealant completely covers both mating surfaces
- Step 8 Inspect to see if all fasteners have been correctly installed. Inspect the back side of the repair to see if the fastener sleeves are satisfactorily formed
- Step 9 Remove and replace any fasteners found to be incorrectly installed
- Step 10 Inspect the edge seal to ensure that there are no gaps to allow moisture to ingress the repair.