STRUCTURAL REPAIRS OF COMPOSITE PARTS

or

WHY CAN'T WE JUST USE BONDO™TO FIX EVERYTHING?

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Structural Composites

The basic strength and stiffness of composite materials suggests that they are often used in some type of structural application, that is, they carry a load or must meet some other engineering mechanical requirements. This use of composites in structural applications applies to both advanced composites and engineering composites. Advanced composites are those usually made with carbon or aramid (such as Kevlar™) fibers and a high performance resin such as epoxy. Engineering composites are those made with fiberglass and resins such as polyester and vinyl ester. Advanced composites are also characterized by the high efficiency of their structure, that is, the careful control of weight and fiber direction to maximize the performance of the composite with minimum weight.

Composite structures subjected to very heavy loads are often called "primary" structures and have traditionally been more common in advanced applications than in fiberglass, especially when efficiency of performance is also an important factor. In particular, these primary structures have been successfully utilized in the aerospace industry for many years. Experiences gained in designing, manufacturing, and repairing these high performance products can serve as tutorials for other segments of the composite marketplace, such as fiberglass composites, thus facilitating the use of fiberglass composites in heavily loaded applications. We are currently seeing a rapid acceleration of the use of fiberglass composites in primary structures, including such civil engineering/infrastructure structures as bridges and highway support columns.

Many advanced composite industrial and civil engineering structures are now quite similar in design and fabrication to aircraft structures, with carefully optimized laminate schedules and ply orientations, and improved process control during manufacturing, including prepreg or resin injection of fiber preforms, vacuum bagging, and oven or occasionally autoclave curing. The resulting products are strong, lightweight laminates with high fiber-to-resin ratios. Laminate thickness is being reduced with these materials and processes, and thin-skinned cored structures, using honeycomb, foam or balsa wood cores, are becoming more popular.

While these can be excellent structures from many points of view, they do tend to suffer from some of the same problems that the aerospace industry has been struggling with for many years. One of the most common problems is impact damage, often from seemingly minor impacts such as dropping a tool on a surface. Of course, heavier impacts, such as from vehicles, or environmental damage (commonly from alkali attack on some types of fiberglass), fire, or UV exposure, can lead to significant and widespread areas of damage.

Damage and Repair

This article will address the repairability issues involved in heavily loaded structures, where the repair has to successfully carry significant loads for long periods of time, and where the consequences of failure are high. We will not address here cosmetic repairs or repairs to lightly loaded non-structural parts.

In the earlier days of composite aircraft structures, it was common to design and build the structures with very conservative assumptions about material strength and durability, due to the significant variation in material properties, and the many unknowns concerning longevity. Hence, safety or engineering factors were high. In these traditional "overbuilt" structures, there lies a tremendous advantage - inherent damage tolerance.

As engineers have become more comfortable with composites, and as design allowables are becoming better understood, the newer structures are being designed to operate closer to the true limits of the composite materials. They are, therefore, lighter and cheaper, since we pay for these materials by the pound. This has a significant implication for "better-designed" advanced composite structures - as we get closer to the actual performance limits of the materials, with smaller safety factors, their inherent damage tolerance is reduced.

This also implies that as damage tolerance is reduced, repairs to damaged structures have to be more than just "patches." They have to actually return the structure to very nearly its original design strength, as the rest of the structure cannot just "pick-up" the load. As the "true" strength limits of the material are approached in very "well-designed" structures, the more critical and difficult repairs must become if the structure is to retain its full load-carrying capability throughout its lifetime.

The design is further complicated by the fact that some composite materials are especially poor at withstanding impact damage. Carbon fibers are notoriously brittle, and structures made with them fare poorly under impacts. If a carbon fiber structure is loaded to a high percentage of its actual load-carrying capability, when it is damaged it tends to fail suddenly and catastrophically.

Structures containing aramid fibers, by themselves or hybridized with fiberglass, tend to be more impact-resistant and yield or give somewhat before failing outright. However, while this may mean that a physical defect is less likely for a given impact, these greater energy absorption capabilities can also lead to a larger physical area of delamination damage than one might see in a brittle carbon fiber structure, resulting in a larger repair. As always in engineering, everything we do involves trade-offs.

Damage Assessment

First we have to gain access to the structure to inspect for the extent of the damage. One of the well-known and difficult problems with any composite structure is the “hidden damage” issue. Some impact damage, especially “light impact,” may be barely visible on the surface but could have considerable matrix cracking and fiber breakage below the surface. The damage will typically spread in a cone-shaped area away from the impact point, and extensive delamination can occur towards the back side of the laminate.

With a moderate impact, there will be obvious crushing and fiber breakage on the surface, and with a severe impact, a torn and ruptured composite surface will be apparent.

After paint or gel coat is removed (by gentle grit-blasting or sanding, not by chemical paint strippers,) the surface should be “tap tested” or “hammer sounded” to help determine the extent of the damage. Gentle taps, with a 50 cent piece or a small ball-peen hammer allow the damaged area to be located because the damaged areas sound different (less ringing) than non-damaged areas. (Remember we are working here on a relatively heavily-loaded, possibly thin, low resin content, advanced composite structures, not two inches of solid mat and woven roving.) Pounding on it with a claw hammer is not a good idea! One can take a small area of damage and turn it into a big one with over-enthusiastic tap-testing.

If back-side access is possible, tap both sides of the composite structure. You will almost certainly find a different and larger pattern of delaminations on the back side. Tap gently back and forth until you can just barely detect a subtle change in tone, from a clear sharp “ring” to a duller “thud”. Back off a bit , maybe ½” or so, and make a mark with a felt-tip pen. Move over an inch or so, and do it again. Soon you will have outlined an irregularly-shaped area of damage.

This inspection method actually works quite well in the type of structure we are concerned with here, but is clearly limited to small areas where damage is already suspected. If a very large area needs to be inspected, tapping gets tedious in a hurry. So for large areas, such as a survey of an entire bridge deck, other inspection methods, such as thermal imaging, may be much more appropriate.

Removal of the Damaged Material

After the inspection and damage determination is completed, the marked area of damage may or may not need to be removed. Two main categories of repairs are usually considered: external doublers (either bonded or bolted) or flush-type bonded repairs (usually into a *scarfed* or *stepped* repair area). These terms will be clarified below.

A doubler means that the repair is added to the thickness (thus, at least conceptually, doubling the amount of material). Often, especially in thick solid laminates where the composite can tolerate a bolt repair, simply covering the damaged area with another pre-cured composite laminate section or, perhaps, a piece of sheet metal is both effective and sufficiently strong to give a long term structural repair. Close-tolerance bolt holes must be used, and careful attention to overlap distance, fastener size, numbers of rows of fasteners to be used, and edge distance, as well as corrosion problems, if carbon fiber composites are used, must all be considered.

(Insert picture of bolted repair here)

For scarfed or stepped adhesively bonded repairs, the damage will need to be removed. Damage removal is usually done either by grinding or routing (cutting). When cutting, use a wheel or circular saw if possible and avoid cutters with reciprocating blades, as in a jigsaw. (The rapid up-and-down motion of a reciprocating blade saw causes delaminations along the edges of the cut.) The best cutting technique is “high-speed, low feed.” This means use a high blade speed or RPM, and gentle pressure, moving along the cut at a low feed rate.

It is best to remove damage in an oval or circular fashion, so as to avoid stress concentrations at corners. If it is necessary to have an odd-shaped damage removal area, ensure that the corners have as large a radius as is practical, and avoid sharp corners at all costs. We will go into quite a bit of detail concerning these types of repairs, to better illustrate the detailed concepts involved.

(*Insert drawing showing squared off vs. rounded corners)*

For carbon fiber structures, a diamond grit-edge blade is best. They are expensive but last a long time, and the “cost per cut” is the cheapest of any blade. Carbide blades will last a little while, and ordinary high-speed steel blades will be dulled to uselessness almost immediately.

For aramid fibers, the best damage removal cutting, with minimum "fuzzing" is achieved with a "split helix" router bit, operated at high speed, typically between 20,000 and 27,000 RPM. A "reversed" steel toothed blade in a circular saw may also be used. For more information on aramid cutting, drilling, routing, machining, etc., including suppliers of specialty bits, call DuPont at 1-800-4KEVLAR and ask for their free cutting and machining manual.

Repair Design

After the damaged areas are completely removed, the new repair material can be applied according to the repair design. In an "ideal" repair, we are trying to match, not exceed, the original structure's strength, stiffness, and weight. There are obviously other concerns, such as a good long-lasting adhesive bond, the smoothness of the repair, the cosmetic appearance, etc., but structurally – matching strength, stiffness, and weight – are the goals.

In any composite design (including for repairs), it is important to realize that the fibers carry most of the load. The matrix resin is weak, brittle, and serves primarily to transfer the load uniformly through the fibers, keep them in alignment, prevent them from buckling under compressive loads, give the part a shape, and protect from the environment. These are all important, but it's still the fibers that carry the actual structural loads.

In a high-performance advanced composite structure, the fibers are oriented in specific orientations to carry the design loads. The only way to get a repair to carry these same loads is to match the ply orientations of the original structure with the repair plies. Therefore we must be able to determine what the original ply orientations were. In addition, we must know what the original materials were. In the preferred repair design, we will match, ply-by-ply, the original structure exactly.

Moreover, we must be able to transfer the loads in the remaining original structure into the repair plies, and back out again. The most efficient way to do this is through a large adhesive bonding area which attaches the repair to the non-damaged structure. *(Insert drawing showing how bonded joints transfer loads)*

The best way to achieve a large bonding area is by creating a very gradual, flat taper (called a scarf) as the interface between the repair and the non-damaged area. This is most often done by sanding away from the edges of the prepared hole. "Stepping" may occasionally be used instead of scarfing, but stepping induces stress concentrations at the corners of the steps, and is also very difficult to perform without damaging underlying plies.

In conventional marine structures, taper angles of anywhere from 7:1 to 14:1 (length to thickness) seem to be used. In heavily loaded advanced composite structures, flatter angles are often used, anywhere from 20:1 to 60:1 being common. Sometimes aircraft repairs will go out as far as 100:1. Obviously, the flatter the taper angle, the more surface area for the bond, and the more gradual the load transfer from the original structure into the repair plies and back out again. If we did a relatively flat scarf, say at 40 to 1, and exactly matched the original ply layup sequence, we get back somewhere between 60% and 80% of the original strength (tensile, compressive, and shear) of the part. So for a .25 inch thick skin, a 40 to 1 taper gives a scarf length of .25 x 40, or 10 inches (on all sides of the damaged area). *(Insert drawing showing scarf distances)*

We do not get back full strength in the above example because we are now working with cut fibers, which must transfer their loads through a new structural adhesive bond, which did not exist in the original structure. The fibers themselves do not cross the bondline. To get back to 100% strength, we would have to do it by adding extra repair plies. This increases the weight and thickness of the repair.

Bending stiffness, however, is more a function of the *thickness* of the structure with some dependence on the type of matrix and the type of fiber (carbon being much stiffer than fiberglass or aramid). All else being equal, bending stiffness goes up approximately with the third power of the increase in thickness. This means that if your repaired area is the same thickness as the original structure, it will have about the same bending stiffness. But if the repair is twice as thick, it will be about *8 times* as stiff! So a full-*strength* repair, attained by adding extra repair plies, will be *stiffer* than the original. This may be fine, or it may be a disaster!

This means we have to carefully consider whether the structure we are repairing is strength-critical or stiffness-critical. If tensile and/or compressive strength are most important, say in a structural column, then a repair which is stiffer than the original will probably be fine, as long as the compliance requirements, perhaps in an earthquake, are considered.

However, a helicopter rotor blade experiences large bending loads, and an overly stiff repair halfway out on the blade would be a really bad idea, and would induce large stresses around the periphery of the repair, possibly leading to premature failure.

To give an extreme example of a stiffness-critical structure, consider a pole vaulter's pole. In use, it is bent through an extreme angle, and of course is also experiencing compression and tension loads. If it was damaged and repaired, one would have to be very careful to not create a stiff spot, which would cause the pole to unnaturally flex just at the edges of the repair. Such a "stiffness discontinuity" would cause the pole to fail at the edges of the repair, at a much lower bending load than normal. Therefore, in repairing a pole vaulter's pole, a very large flat scarfed area would be used with a low taper angle. Such a technique is sometimes called "reathering." Furthermore, the thickness would be carefully matched which would usually result in a decrease in tensile and compressive strength. *(You may want to use some or all of the drawings marked "Scarfed repairs - or not!)*

Repair Bonding

Since heavy structural loads must be transferred across the repaired area through the scarfed bondlines, the adhesive bond itself must be structural. The type of adhesive is important, as is the preparation of the surfaces to be bonded. There is no ideal adhesive that will solve any bonding problem. However, epoxies, and acrylics and their derivatives, such as methacrylates, are generally the best for most repair purposes. Polyester resin does not make a good structural adhesive.

Epoxies, while they can be very strong, are intolerant of dirty surfaces, and meticulous surface preparation is crucial to achieving a long-lasting bond. One point perhaps not well understood about epoxies is that the greatest importance of a contaminated surface is over time, especially when exposed to water, because bond strengths deteriorate much more rapidly when the initial surface preparation was poor, than with properly prepared surfaces. The difference between a structural bond which lasts one year, and one that lasts 30 years, can literally be the difference in what type of rag you used in solvent wiping, or in the cleanliness of the solvent itself.

Surface preparation for bonding is actually a long and involved subject, with many subtle points just now being well understood, and is properly the subject of its own article. But briefly, be very clean in everything you do to the scarfed surface. Do NOT blow compressed air on it to blow off the dust. Compressed air is full of oil and water. Use clean, reagent grade solvents, and clean, one-use only, disposable rags. Don't touch the surface with your fingers after scarfing unless you have on clean gloves. Make sure the surface is thoroughly dry before applying adhesive, and protect the cleaned surface with a taped-on piece of kraft paper when you take a break between steps.

The basic sequence for conducting a repair is summarized in Table 1.

It may seem from all this, that repairing strong but lightweight composites is a difficult, time-consuming, pain. That's only because it is! However, without the old tremendous safety margins that are one of the best features of "old-fashioned" composite structures, we do have to be much more careful and detail-oriented in these repairs. Slapping on some woven roving and mat and polyester resin just won't work in structural applications, and such repairs will fail, with Murphy watching to make sure they fail at the worst possible time.

Doing it right is not difficult – just time-consuming, and requirs a level of training and attention to detail that may take some getting used to. But it is possible to repair these critical structures correctly, and with good confidence, the repairs will last. It's has been done every day in the aircraft business for many years, and is already being done in the marine industry very commonly. These structures are probably not a passing and those who learn to deal with them now will be well placed for the rapid growth of this technology in the future.

Table 1 – Steps in Making a Structural Composite Repair

- Damage the part (you may omit this step if you wish!)
- Gain access to the part – both sides if possible
- Clean and dry the surfaces
- Remove any gel coat and/or paint by careful mechanical abrasion, not with paint strippers.
- Inspect for damage visually and by tapping
- Mark out the damaged areas
- Remove the damaged structure. If it is a thick structure, and the damage is not all the way through, then you may grind away the damaged plies until solid plies are reached.
- Carefully taper (scarf) sand away from the edge of the damage, at least at a 12 to 1 taper for lightly loaded structures, up to 40 to 1 for heavily loaded structures.
- Ensure that the scarfing is done slowly and carefully by a skilled artisan - this is no time for Tim the Toolman. Let Al do the work.

- After the scarfing is completed, cover the surface with a smooth, taped-down sheet of clear kraft paper or plastic film to protect it from dirt, moisture, grubby fingers, etc.

- Trace out on additional pieces of clear film the outline of each repair ply, so they neatly fit in the "contour map" created on the surface by your scarfing.

- Mark on the templates the ply orientation of each ply as you trace its outline.

- Cut out replacement plies from the same material as the original structure. If this is not available, you may be able to talk to vendors and find a close substitute. Don't wing it here. You need the original materials or very close substitutes. Remember, we're talking about a heavily loaded, lightweight, structural repair with small safety margins.

- If you're working with prepreg, apply a layer of film adhesive to the entire CLEAN scarfed area. If you're doing a wet layup, apply a thin layer of your epoxy resin to the scarfed surface.

- Lay down the innermost, smaller ply first. If you have a hole through the structure, you'll need to back up the hole with a released caul plate on the back side if you have back side access. If you don't have back side access, then one technique is to bond on, through an oval hole rather than circular, a larger oval on the backside to act as a back side support for the "filler" ply.

- Continue to lay up a ply at a time, working up toward the larger surface plies, being careful to match the ply orientations of the original structure as you go.

- Once the top ply is in place, add any extra repair plies, with each extra ply about ½ inch larger all the way around than the original top ply. The ply orientation of the extra ply or plies should match the original outer ply.

- You may also wish to add a sacrificial outermost ply of thin fiberglass to act as a sanding ply.

- Vacuum bag the repair using standard bagging techniques. *NOTE TO BRENT STRONG: VAC BAGGING IS A SUBJECT FOR ANOTHER ARTICLE, AND THIS ONE IS TOO LONG ALREADY!* Note - If you are using prepregs, and if the repair has more than about four or five plies, or if it has a complex contour, then we strongly urge intermediate "debulk" steps using a vacuum bag, to pre-compact and consolidate the plies.

- Cure the repair, at high temperature if required, in a controlled oven situation if possible, or CAREFULLY using heat lamps or heat guns and multiple thermocouples to monitor and control temperatures evenly. If you are doing a room-temperature wet layup, most structural epoxies still require a high-temperature post-cure to develop full strength in a reasonable time. However, some epoxies can be fully cured to reasonable strength numbers at room temperature, and these may be fine if high temperatures will not be encountered by the repaired structure in service.

- After the cure is completed, debag the repair, and inspect it for delaminations, disbonds, or other unpleasantries. Clean it up, carefully sand it smooth (don't cut fibers in the top ply, unless it is a sacrificial sanding ply), and paint it or gel-coat it as appropriate.