Module – 8: Design Concepts

Learning Unit-1: M8.1

M8.1 Design Issues

M8.1.1 Introduction to Design

The design of composite structure is complicated by the fact that every ply must be defined. Drawings or design packages must describe the ply orientation, its position within the stack, and its boundaries. This is straightforward for a simple, constant thickness laminate. For complex parts with tapered thicknesses and ply build-ups around joints and cutouts, this can become extremely complex. The need to maintain relative balance and symmetry throughout the structure increases the difficulty.

Composites can not be designed without concurrence. Design details depend on tooling and processing as does assembly and inspection. Parts and processes are so interdependent it could be disastrous to attempt sequential design and manufacturing phasing.

Another factor approached differently in composite design is the accommodation of thickness tolerances at interfaces. If a composite part must fit into a space between two other parts or between a substructure and an outer mold line, the thickness requires special tolerances. The composite part thickness is controlled by the number of plies and the per-ply-thickness. Each ply has a range of possible thicknesses. When these are layed up to form the laminate they may not match the space available for assembly within other constraints. This discrepancy can be handled by using shims or by adding "sacrificial" plies to the laminate (for subsequent machining to a closer tolerance than is possible with nominal per-ply-thickness variations).

The use of shims has design implications regarding load eccentricities. Another approach is to use closed die molding at the fit-up edges to mold to exact thickness needed.

The anisotropy of special laminates, while more complicated, enables a designer to tailor a structure for desired deflection characteristics. This has been applied to some extent for aeroelastic tailoring of wing skins.

Composites are most efficient when used in large, relatively uninterrupted structures. The cost is also related to the number of detail parts and the number of fasteners required. These two factors drive designs towards integration of features into large cocured structures. The nature of composites enables this possibility. Well designed, high quality tooling will reduce manufacturing and inspection cost and rejection rate and result in high quality parts.

M8.1.2 Design issues and guidelines

M8.1.2.1 Laminate Stacking sequences (LSS)

When impact damage is dominated by fiber failure, it is desirable to stack primary load carrying plies in locations that minimize fiber failure. Since fiber failure typically occurs first near outer surfaces, primary load carrying plies should be concentrated towards the center of the LSS. Experience to date suggests that a homogeneous LSS might be best for overall CAI performance dominated by matrix damage.

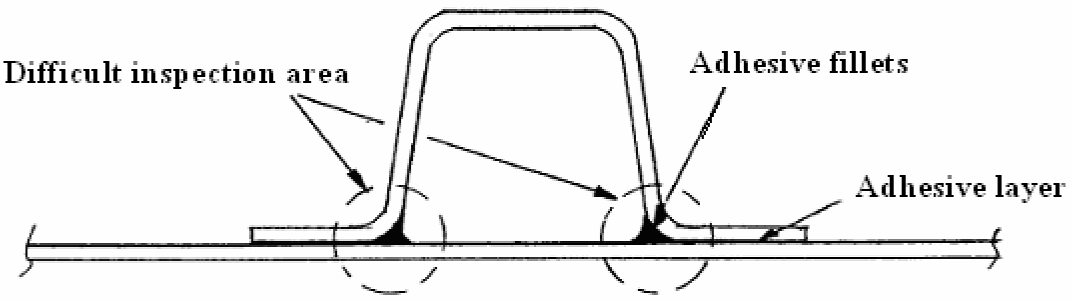
M8.1.2.2 Sandwich structure

Caution should be applied when using sandwich material combinations where significant impact damage can occur within the core, without visible surface indications in the facesheet (This type of impact critical damage state (CDS) has been identified for certain types of honeycomb and foam cores.). This is particularly true for compressive or shear loaded structures in which such damage may grow undetected to critical sizes. Simple impact screening tests can be used to identify this failure mechanism and the related drops in residual strength.

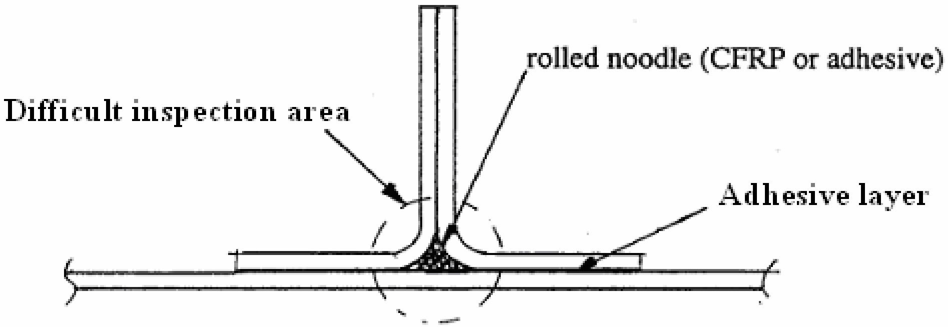
M8.1.2.2.1 General Design guidelines

Whether one chooses a laminate stiffened skin or a sandwich configuration for a specific component, there are inspect-ability issues within each configuration category. For example, the use of closed hat stiffeners to stiffen laminate skins, while extremely efficient from a structural point of view, create three areas in the skin and stiffener that are difficult to inspect by any method (Figure 8.2.2.1(a), section (a)). A blade stiffener, on the other hand, has only the one difficult inspection area (Figure 8.2.2.1(a), section (b)). The adhesive fillets of the closed-hat stiffener, and the rolled noodle of the blade stiffener, are contributors to these inspection difficulties. These areas are difficult to inspect during the manufacturing process, and are even more of a problem for the service operator with limited access to the internal surfaces.

With a sandwich configuration there are inspection difficulties associated with potted areas, detection of fluids that have leeched into the sandwich honeycomb core, disbonds of face sheets, foam core, and damages within the core. Also difficult for operators are inspections of bondlines of stiffeners or frames that are bonded to the internal face sheets of sandwich components (Figure 8.2.2.1(b)). When airplane operators are forced to use inspection methods that are subjective, i.e., the tap test, they are handicapped by lack of knowledge of damage sizes and criticality. This is a significant problem for operators, and while sandwich structural configurations can be very efficient from a performance point of view, they tend to be fragile, easily damaged, and difficult to inspect. Interestingly some airline operators prefer sandwich over laminate stiffened skins from a repair point of view, but virtually all express frustration with the durability and inspection of sandwich structures.



(a) Closed-hat stiffened configuration



(b) Blade stiffened configuration

Figure 8.2.2.1 (a) Difficult to inspect areas on laminate skin stiffened designs.

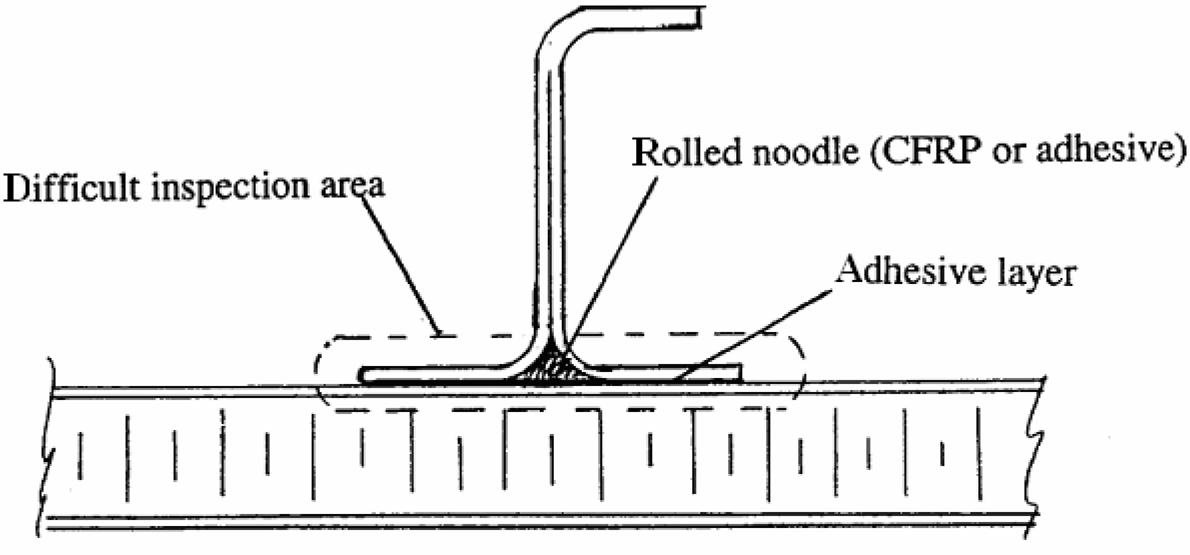


Figure 8.2.2.1 (b) Difficult inspection area of sandwich structural configurations.

Most composite structural components will include metal fittings or interfaces with metal parts. It is desirable to ensure that these metal parts can be visually inspected for corrosion and/or fatigue cracking. In addition, if the mating metal parts are aluminum, then it is important to be able to inspect them for potential galvanic corrosion that may be caused by contact with the carbon fibers. This may require removal of fasteners at mating surfaces, so blind fasteners should not be used in these applications. The use of blind titanium fasteners should be kept to a minimum because, when installed, they are literally impossible to inspect to verify correct installation. They are also very difficult to remove when repairing or replacing a component.

M8.1.3 Design guidelines

Laminate design starts by selecting the number of plies and ply angles required for a given application. Once the number of plies and ply angles are selected, a LSS is chosen. A LSS is considered heterogeneous when there is preferential stacking of specific ply orientations in different locations through the thickness of the laminate. Thick laminates with heterogeneous LSS are created by clumping plies of similar orientation. A LSS is said to be homogeneous if ply angles are evenly distributed through the laminate thickness. The ability to generate homogeneous LSS depends on the number of plies and ply angles. For example, it is impossible to create a homogeneous LSS for a four-ply laminate consisting of four different ply angles.

The following LSS guidelines are based on past experience from test and analysis. Guidelines are lumped under two categories: (1) strong recommendation, and (2) recommendation. Despite this classification, exceptions to the guidelines should be considered based on an engineering evaluation of the specific application.

M8.1.3.1 Strong recommendations

1. Homogeneous LSS are recommended for strength controlled designs (In other words, thoroughly intersperse ply orientations throughout the LSS).

> **Comment:** Heterogeneous laminates should be avoided for strength-critical designs unless analysis and test data is available that indicates a clear advantage. In cases where **heterogeneous laminates** cannot be avoided (e.g., **minimum gage laminates**), it is generally best to stack primary load-carrying plies toward the laminate core. The best way to view possible strength problems with heterogeneous LSS is to consider the behavior of individual sublaminates (i.e., groups of plies separated by delaminations) that may be created during manufacturing or service exposure. This will be discussed later in greater detail.
>
> Heterogeneous LSS can yield optimum stiffness or stability performance; however, the effects on all other aspects of the design (e.g., strength, damage tolerance, and durability) should be considered before ignoring Recommendation 1. For example, interlaminar stress distributions are affected by variations in the in-plane stress field around the periphery of holes and cutouts and the "effective" LSS (i.e., ply orientations relative to a tangent to the edge). Since it is difficult to optimize for a single lay-up in this case, the best solution is to make the LSS as homogeneous as possible.

2. A LSS should have at least four distinct ply angles (e.g., 0°, ±θ°, 90°) with a minimum of 10% of the plies oriented at each angle. Ply angles should be selected such that fibers are oriented with principal load axes.

    Comment: This rule is intended to avoid the matrix-dominated behavior (e.g., nonlinear effects and creep) of laminates not having fibers aligned with principal load axes. Such behavior can lead to low strengths and dimensional stability problems.

3. Minimize groupings of plies with the same orientation. For tape plies, stack no more than four plies of the same orientation together (i.e., limit stacked ply group thickness ≤ 0.03 in. (0.8 mm)). In addition, stacked ply group thicknesses with orientations perpendicular to a free edge should be limited ≤ 0.015 in. (0.38 mm).

    Comment: This guideline is used for laminate strength-critical designs. For example, it will help avoid the shear-out failure mode in bolted joints. It also considers relationships between stacked ply group thickness, matrix cracking (i.e., transverse tension and shear ply failures) and delamination.

    In general, ply group thickness should be limited based on details of the design problem (e.g., loads, free edges, etc.) and material properties (e.g., interlaminar toughness). Note that the absolute level of ply group thickness identified in this guideline is based on past experience. It should be confirmed with tests for specific materials and design considerations.

4. If possible, LSS should be balanced and symmetric about the midplane. If this is not possible due to other requirements, locate the asymmetry or imbalance as near to the laminate midplane as possible. A LSS is considered symmetric if plies positioned at an equal distance above and below the midplane are identical (i.e., material, thickness, and orientation). Balanced is defined as having equal numbers of +θ and - θ plies, where θ is measured from the primary load direction.

    Comment: This guideline is used to avoid shear/extension couplings and dimensional stability problems (e.g., warpage which affects component manufacturing tolerances). The extension/bending coupling of unsymmetric laminates can reduce buckling loads. Note that some coupling may be desired for certain applications (e.g., shear/extension coupling has been used for aeroelastic tailoring).

M8.1.3.2 Recommendations:

5. Alternate + θ and - θ plies through the LSS except for the closest ply either side of the symmetry plane. A + θ /- θ pair of plies should be located as closely as possible while still meeting the other guidelines.

> **Comment:** This guideline minimizes the effect of bending/twisting coupling, which is strongest when angle plies are separated near the surface of a laminate. Modifications to this rule may promote more efficient stiffness and stability controlled designs.

6. Shield primary load carrying plies from exposed surfaces.

   > **Comment:** The LSS for laminates primarily loaded in tension or compression in the 0° direction should start with angle and transverse plies. Tensile strength, micro-buckling resistance, impact damage tolerance and crippling strength can all increase by shielding the main load bearing plies from the laminate surface. With primary load fibers buried, exterior scratches or surface ply delamination will not have a critical effect on strength. For laminates loaded primarily in shear, consideration should be given to locating +45° and -45° plies away from the surface. For cases in which an element is shielded by other structures (e.g., **shear webs**) and it may not be necessary to stack primary load carrying plies away from the surface.

7. Avoid LSS that create high interlaminar tension stresses (σ_z) at free edges. Analyses to predict free edge stresses and delamination strain levels are recommended to help select LSS.

   > **Comment:** Composite materials tend to have a relatively low resistance to mode I delamination growth. Edge delamination, followed by sublaminate buckling can cause **premature failure** under compressive loads. Edge delamination occurring under tensile loads can also effectively reduce stiffness and lower the load carrying capability. Since delaminations occurring at the core of the laminate can have the strongest effect on strength, avoid locating tape plies with fibers oriented perpendicular to a free edge at the laminate midplane.

8. Minimize the Poisson's ratio mismatch between adjacent laminates that are co-cured or bonded.

   > **Comment:** Excessive property mismatches between cobonded elements (e.g., skin and stringer flange) can result in delamination problems. In the absence of more sophisticated analysis tools, a general rule of thumb is

$$\left|\nu_{xy}(\text{laminate 1}) - \nu_{xy}(\text{laminate 2})\right| < 0.1$$

As opposed to static strength, composites are not particularly notch-sensitive in fatigue; hole wear is often used as the governing criterion constituting fatigue failure of composites loaded in bearing.

M8.1.4 Rules and Design Heuristics

A comprehensive structural analysis program for designing composite laminates is quite extensive and cumbersome because this generally involves several analysis phases such as laminate stress and strength analysis. Hence, there is still a need for the designer to have some preliminary knowledge of the lay-up sequence of composite laminates before any such analysis is actually conducted. A simple trial-and-error program is insufficient for this purpose.

Generally, structural properties of composite laminates such as stiffness, strength, and dimensional stability have all been found to depend on the laminate stacking sequences. Because each property has different relations with a particular stacking sequence, the choice of stacking sequence suited for a particular application may entail a compromise.

The rules and design heuristics to reduce undesirable stress coupling are as follows:

1. A laminates stacking sequence should be symmetric about the mid-plane to avoid extension-bending coupling.
2. A laminate stacking sequence should be balanced to avoid shear-extension coupling.
3. ±θ plies should be grouped to reduce bending-twisting coupling.

The rules of design heuristics to improve strength are as follows:

1. Homogeneous lay-up is recommended for strength-controlled design. Heterogeneous laminates should be avoided for strength-critical designs. In the case where heterogeneous laminates cannot be avoided, it is generally best to stack primary load-carrying plies toward the laminate core.
2. Minimize groupings of plies with same orientations to create a more homogeneous laminate and to minimize interlaminar stress and matrix cracking during the service period. If plies must be grouped, avoid grouping more than four plies of the same orientation.
3. Avoid grouping of 90° plies and separate 90° plies by a 0° or 45° ply to minimize interlaminar shear and normal stress.
4. Separate ±θ plies to reduce interlaminar shear stress.
5. Shield primary load carrying plies by positioning inside of laminate to increase tensile strength and buckling resistance.
6. To avoid large-scale matrix cracking and delamination, the ply angle difference between the adjacent plies must not exceed 45°.
7. Avoid positioning tape plies with fibres oriented perpendicular to edge at the laminate mid-plane to lessen high interlaminar at free edges.
8. If tape plies with fibres oriented perpendicular to a free edge should be stacked at mid-plane, stack no more than approximately three plies.
9. When there exits a hole, avoid locating tape plies with fibres oriented perpendicular to loading direction at the laminate mid-plane to lessen interlaminar stress around a hole.

The above rules of design heuristics should be carefully applied according to loading and conditions.

Learning Unit-2:M8.2

M8.2 Typical Structural Component Design Process

M8.2.1 Joining Composite Materials — Mechanical or Adhesive

The Achilles heels of composite structures are the joints. (Aren't heels joints?) Many designers will tell you that designing the composite laminate is fairly simple, but that far more time is devoted to the designing of the joints. The joints connect laminate sections together; provide mechanisms for the inclusion of secondary structures, such as fittings, ribs, bosses, and dividers; and connect the composites to surrounding structures — metals, wood, ceramics, plastics or other composites. While the primary purpose of joints is structural, they may have other functions such as electrical or thermal conductor or insulator, sealant, or vibration damper. The variety of applications of joints is, in part, the problem. A single joining method simply cannot be applied overall. Hence, in complex structures, many different joining methods could be used at the same time. However, each particular instance can usually be considered separately, thus reducing even the most complex composite structure to a series of individual joining situations.

Typically, there are two basic joining methods - mechanical and adhesive. These are generally used independently in each joint, but can be combined to achieve special benefits, as will be discussed later in this article. The choice between mechanical joining and adhesive joining is one of the major decisions which must be made. The characteristics of each of the systems are briefly summarized in Table M8.2.1.

Mechanical Joining

The basic method of mechanical joining is done by drilling holes in the two materials to be joined (such as two composite laminates) and then placing a mechanical fastener through the holes and fixing the fastener in place. The types of fasteners usually dictate the fixing method. For instance: bolts are fixed with nuts, screws are fixed through the interaction of the threads and the materials to be bonded, rivets are fixed by heading the rivet itself, and pins are fixed by simple interference with the holes.

Because these methods do not rely upon the nature of the surfaces of the materials being bonded, little or no surface preparation is required. The only dependence on the materials is the strength of the materials at the joint location. For instance, if the materials are crushed easily, bolts and nuts may exert too much compressive force and the materials could be deformed. Also, if the materials are not strong in shear, screws may not hold.

Drilling the holes can cause delamination of composites. This drilling should be done with proper backing and support and in consideration of the type of composite material being drilled (Kevlar®, fiberglass, and carbon fibers behave quite differently during drilling and require different drill configurations). Additional problems with mechanical fastening can arise because of the cutting of the fibers which must occur when the holes are drilled to accommodate the fasteners. These problems arise especially if the composite has been closely designed to the limits of performance. Good joint design will overbuild in the joint region, usually by increasing the number of fibers. This can be done by using more composite material (thicker joint areas), by adding additional or longer fibers (adding cloth or unidirectional fibers in the joint area), or by reinforcing with a non-composite material such as a strip of wood or metal.

Mechanical fasteners create point loads at the contact points. These localized forces may cause localized failure. Point load failures are usually prevented in the same way that failures from drilling holes in the laminate are prevented (thicker materials, added reinforcements). Therefore, a primary consideration in choosing mechanical joining is whether the materials are strong enough to withstand the forces exerted by the mechanical fasteners themselves or whether they can be easily improved in the critical region.

The long term effects of mechanical fasteners in joining composites have not been fully explored. Some of the long term considerations include fatigue because of the point loads in particular, corrosion between the fasteners and the composite (especially true in carbon fiber composites joined with aluminum), and admission of moisture through the joint itself.

Mechanical fasteners withstand peel forces well, but do not contribute significantly to tensile forces. These forces and the others important in joint design are illustrated in Figure M8.2.1. Mechanical joints have poor performance in tensile. The tensile loading situation can be simulated by a simple example. Imagine, for instance, two standard sheets of paper that have three staples joining them across the bottom of one sheet and the top of the other. If the sheets are then pulled in tension, they will deform, load at the staples disproportionately, and separate at the staples. Composite laminates behave similarly.

Mechanical fasteners are typically metallic and therefore increase the overall weight of the joint, especially because the mechanical fasteners are often closely spaced to reduce the problem of poor resistance to tensile forces. To reduce the weight, light metals such as aluminum or titanium can be used, but at a higher cost compared to the traditional steel fasteners. Some new work in fasteners made of composites has been reported, although they have not yet gained widespread usage.

Lest you think that mechanical joining of composites is all negative, some discussion of the advantages of this type of joining should be made. The mechanical joining system is simple, reliable, proven, and easy to inspect. These are, perhaps, the primary reasons that mechanical joining is still used so extensively. Moreover, mechanical fasteners rarely limit the use temperature of the composite which is, therefore, usually dictated by the composite itself. Adhesive Joining

A wide variety of materials is available when adhesives are used to bond materials together. The choice of which adhesive is best is usually dictated by the type of composite to be bonded, the application of the bonded composite, the service environment, and cost. The general classes of adhesives are: structural, hot melt, pressure sensitive, water-based, and radiation cured.

In general, the structural adhesives dominate when joining of composites is required. The most common polymers in the structural adhesives class are: epoxies, polyurethanes, acrylics, cyanoacrylates, anaerobics, silicones, and phenolics.

The first consideration in choosing an adhesive should be an assurance that the composite and the adhesive are chemically compatible. When compatibility is good, the bonds between the composite and the adhesive are optimized. Generally, the rule of thumb for compatibility is that the closer the chemical nature of the composite resin is to the adhesive, the better the performance.

The choice of adhesive should next be viewed in terms of the service environment. This could include factors such as temperature, solvent and moisture resistance, UV-light exposure, expected service life, and the loads expected during use. No simple rules exist for examining all these factors for each of the available adhesives. Good engineering experience, in consultation with the manufacturer of the adhesive, is often the best way to make the choice.

In some cases, the operational factors in making the bond will strongly dictate the choice. For instance, although all adhesives require excellent surface preparation of the materials to be joined, some adhesives require a stricter regimen than do others. Also, some adhesives are more forgiving in the fabrication of the joint. Some adhesives require little time to form an acceptable joint while others require clamping and exacting cure conditions.

The strength of the adhesive bond requires that the adhesive completely spreads over the surface of the substrates to be joined. This is called wetting the surface. Wetting is improved by chemical compatibility between the surfaces and the adhesive. Wetting is also improved when the bonding surfaces are clean. Bonding is also improved when some mechanical interlocking exists between the adhesive and small irregularities on the surfaces of the materials to be joined. Therefore, the first step in making an adhesive bond is often a roughening of the surfaces to be bonded. This is followed by a cleaning to remove all oils, greases, debris, and other surface contaminants. This cleaning can be very complex, for instance, when oxide layers must be removed from metals. That may require chemical etching, sand blasting, plasma treatment, or other sophisticated cleaning approaches. Following these, metals may need to have a primer applied to both protect the cleaned surface and improve chemical compatibility with the adhesive.

Most adhesive manufacturers will recommend the primer and the surface preparation should these be needed. Once primed and prepared, the time elapsed to application of the adhesive should be kept short.

The adhesive can be applied in many ways. Some are liquids and are often metered onto the surface using a melt pump or other liquid regulating system. Liquid adhesives could, of course, be brushed on or wiped on in situations not requiring high precision of adhesion placement and quantity control. However, remember that the adhesive is generally not reinforced and is, therefore, lower in strength than the typical composite it is joining. Therefore, proper procedure is to use only enough adhesive to completely cover the bonded surfaces. To facilitate the proper application of adhesive quantity, many adhesives can be purchased as films or sheets which are simply laid in place.

Adhesives might also be supplied as pastes or even solids (powdered). These require some special care in ensuring that they are placed correctly. Heat and pressure may be necessary.

After application of the adhesive, the parts to be bonded should be carefully aligned in the designed configuration. They are usually held in place with clamps or some equivalent mechanical restraining device. The parts should then remain in this fixed position until after the adhesive has solidified. Bonding tooling and jigs or fixtures are often utilized at this stage to ensure alignment and proper contact during this stage.

Some adhesives, especially structural ones, are solidified through heated curing. Others adhesives may cure with moisture, evaporation of a solvent, UV-light exposure, or some other sophisticated method. Of course, adhesives requiring only pressure and contact are also known (like Scotch® tape) but these are not often structural.

Obviously, considerable effort is required to insure good adhesive bonding. What are the advantages to be gained from this effort? In aerospace applications, the major advantage is often weight savings. Also, the distribution of the forces over a wide area contributes to the long term performance of the part. Further, moisture and solvent intrusion is often eliminated by the self-sealing nature of many adhesives. Many adhesives are quite flexible when compared to the composite materials they are joining, thus providing shock and vibration reduction.

An issue not often appreciated is the ability of adhesive materials to join together complex shapes. Related to that is the ability of adhesive to join thin sheets through their natural distribution of forces.

Some composite fabricators have been successful in reducing operation times by applying the adhesive to an incompletely cured composite laminate and then co-curing both the laminate and the adhesive. This not only reduces fabrication time, it also generally improves bond strength.

Combination of Mechanical and Adhesive Joining

Do you use both a belt and suspenders? Fears of failure for one or the other joining methods lead some fabricators into dual application of joining methods. There are, however, some occasions when application of both a mechanical joining device and an adhesive are required. For instance, if the interface is best joined mechanical but a sealed joint is required, then both must be used. Also, fast curing adhesives may be used as a method of rapid assembly before the permanent mechanical joints are installed.

In some applications, the use of an adhesive bonding agent can spread the peak loads inherent in mechanical joints and improve joint performance.

Summary

We have discussed, in general terms, the differences between mechanical and adhesive joining methods. Each has certain advantages over the other, but also has disadvantages. The choice is complex and should be made with careful consideration of the application purpose, the use environment, and the fabrication process. Cost is, of course, a critical consideration, but should be considered in more depth than just the cost of the joining materials.

Acknowledgments

Property	Mechanical Joining	Adhesive Joining
Time to make the joint	Several steps, joint assembly rapid	Few steps, long cure
Surface preparation	Minimal	Extensive, critical
Thin sections	May not be possible	Can be done
Joint weight	Heavy	Light
External surface aspects	Protrusions	Can be smooth
Temperature limitations	Limited by the laminate	Adhesive may limit
Laminate fiber damage	Can be important	Not important
Ability to inspect	Easy	Difficult
Environmental issues	Can have galvanic corrosion	Solvent sensitivity
Moisture penetration	No resistance	Self-sealing
Stress concentrations	Significant	Can be very low
Long term loads	Relaxation and fatigue effects creep	
Sensitivity to peel forces	Resistant	Susceptible
Sensitivity to tensile forces	Susceptible	Resistant
Vibration dampening	No damping	Inherent damping
Health and safety	Cutting, drilling, thermal dangers	Solvent, thermal, dangers

Table M8.2.1: The characteristics of mechanical and adhesive systems

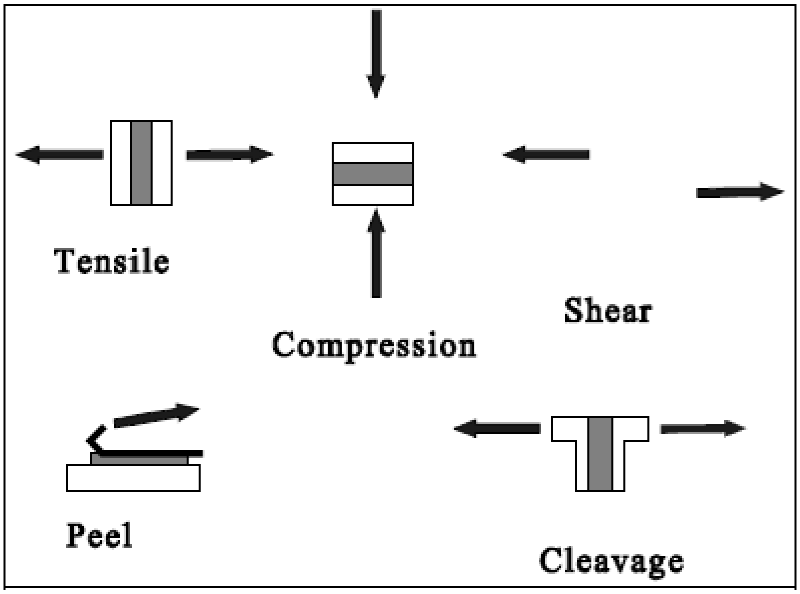


Figure M8.2.1: Peel forces acting on mechanical fasteners (but do not contribute significantly to tensile forces).

M8.2.2 Design of Structures

Structure and Makeup of Composites

The matrix of a composite is the material that binds the reinforcement and holds it together in the desired position as well as transfers the load between the discrete reinforcements. Discontinuous reinforcement in the form of short fibers, whiskers, or particulate inclusions can be used in a metal, ceramic, or polymer matrix. This type of reinforcement usually serves to increase stiffness or toughness of the material but does little to increase the overall strength of the final product. Metal and ceramic matrix composites of this type can perform well in applications where high temperatures or abrasion resistance are critical. Polymer matrix composites with discontinuous fiber reinforcement are common where formability and low cost production are important.

Continuous fiber reinforcement has an entirely different purpose in that it is meant to increase strength and stiffness in the fiber direction. The resulting anisotropic properties can be utilized to reduce the total amount of material used when strength is only needed in certain directions through the part. This type of reinforcement is rarely seen in ceramic matrices because of the brittle nature of most ceramics, but can be used in metal matrix systems. The most common type of continuous fiber reinforced composites are polymer matrix composites. The relatively low mechanical properties of the polymer become insignificant because the entire load is carried by the high strength, high modulus fibers. The primary function of the polymer is to hold the relatively flexible fibers in place and keep them from buckling in compression. Because the matrix does help distribute the load more evenly between the fibers, the bond strength between fiber and matrix is very important. Typical types of fiber used in this sort of application are carbon, organics such as aramid (Kevlar) and polyethylene, and glass. Each of these types of fiber has its own strengths and weaknesses. Carbon fiber reinforced laminates are the strongest in both tension and compression. They also have a very high modulus, but this lack of ductility causes sudden brittle failures at low strain rates. Glass fibers exhibit high strength" in both tension and compression, but their modulus is not as high as carbon or Kevlar because of the lack of a continuous chain, or backbone of carbon-carbon bonds. The amorphous structure adds to compressive strength and transverse properties, but it makes the fibers very brittle and susceptible to cracks that cause high stress concentrations. Kevlar fibers are only slightly behind carbon in tensile properties, but their compressive properties are poor, roughly half of carbon or glass. This is because the Kevlar fibers buckle easily in comparison to the other types of fibers. This disadvantage quickly becomes an advantage when toughness and failure modes are taken into account. The molecular structure of the fiber allows for more distortion in the transverse directions as the fiber is loaded in compression or shear than the straight carbon backbone in carbon fibers or the brittle amorphous glass fibers. This distortion absorbs a considerable amount of energy during failure and makes Kevlar much tougher than the other types of fibers. The problem with Kevlar and polyethylene fibers is that they are polymer based, and usage temperatures must be kept below approximately 120°C to reduce creep. Polyethylene fibers consist of long, tangled polymeric chains, and the strength of these fibers is much lower than the others discussed previously. Their ability to handle large amounts of deformation makes them very tough and fracture resistant. When they are used in combination with the other high strength fibers, these properties can greatly improve the impact resistance of the laminate.

The last part of a composite laminate structure is the core that separates the face sheets. It stiffens the composite in bending by providing a moment of inertia around which the fibers can function in simple tension and compression. The core also carries any shear loading through the thickness of the composite since the fibers have very little strength normal to the axis. Without the core, shear loads would have to be supported by the matrix or the fiber normal to the direction of their alignment. Wood, foam, solid metal and paper or metal honeycombs are all common core materials. The choice of a core material depends on the shear strength, density, and compressive strength dictated by the sandwich design as well as the cost of the material. Wood and foam are generally the lowest cost alternatives, but the strength to density ratio can be less than ideal.

Honeycomb is more expensive, but is very lightweight and the Nomex paper varieties show very good properties. The density of the core is extremely important because a sandwich structure becomes more and more efficient in bending and compression as the face sheets are separated by increasingly greater distances. This requires filling that volume with something strong enough to separate the face sheets, and a lighter core invariably produces a lighter final part.

Design of Composite Structures

Any structure in which the loading throughout the part can be reduced to planar loading in specific directions can benefit from a fiber reinforced composite structure. This includes flat plates, torsion tubes, flexure beams, pressure vessels, etc. A pressure vessel transfers the outward force perpendicular to the vessel walls to a tension in the plane of the wall surface. Torsion tubes and beams support a single axis load by transferring the load to multiple surfaces some distance away from the line of action. As this moment of inertia is increased, the tension surfaces are decreased. The limiting factors are generally the spacial constraints of the part and the weight of the material separating the face sheets, or surfaces. The sandwich style laminate construction allows bending loads to be carried by a relatively small cross sectional area of fiber. Isolated compression and tension loads can be supported only along critical load paths by fibers more effectively than by a solid sheet of isotropic material.

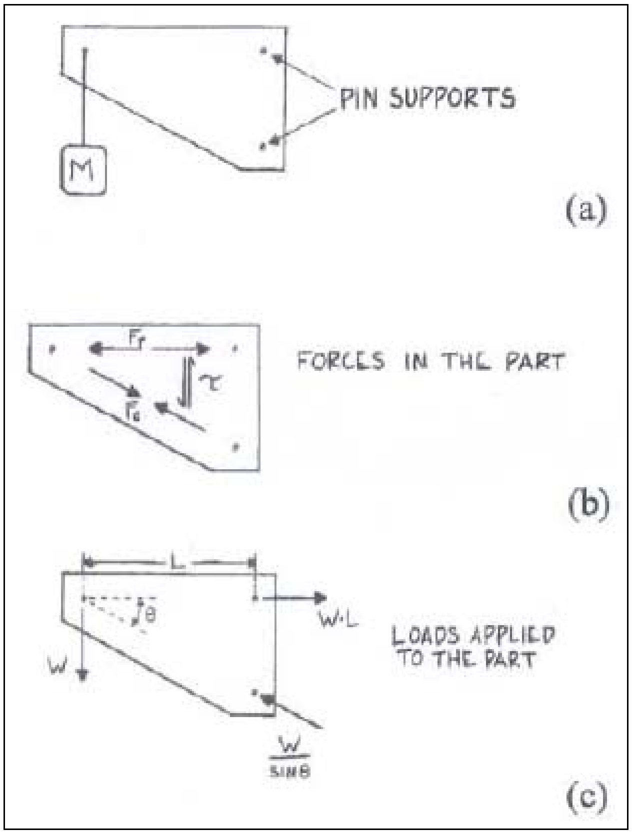


Figure M8.2.1: Steps of designing composite structures.

The first step in designing a composite structure is to determine where the loads enter and exit the part. In the case of a flat plate with pin supports (Figure M8.2.1-a), a load is applied by gravity acting at the attachment point of the mass. The pins the load provides the reaction loads that transfer the forces to the support structure. This causes a tension load to be applied between the top pin and the load point, and a compression load between the bottom pin and the load point (Figure M8.2.1-b). These are the basic load paths in the part, or the directions along which simple truss members could be placed to support the load points. However, there is also a constant shear load along the entire length of the part from the load point to the pins. Calculating the moment from the load, the tension force, F_t, is equal to the lever arm (horizontal distance) times the load perpendicular to that lever arm.

$$F_t = W * L \qquad ......(M8.2.1)$$

The compression force can be found by equating the forces or moments in static equilibrium.

$$F_c = W/sin(\theta) \qquad (M8.2.2)$$

Shear is always equal to the weight of the mass.

$$\tau = W \qquad (M8.2.3)$$

Now we begin to design how we would support these loads. The simplest solution, and the one that occurs first to most people, is to drill holes in a flat metal plate, thick enough to support the tension, compression and shear, but this is not a very effective solution. A more efficient way to support these loads would be to create an I-beam with more material in the areas where the tension and compression loads act and less where the only load is the shear. Even this is less than ideal because metal is isotropic and even by concentrating it along the load paths, the design requires more material than needed. The advantage of fiber reinforced composites is that the high strength and modulus of the fibers along the axis can be used only where and in the directions it is needed to support the load. Since we have already calculated the value of each load, we can use the tensile and compressive properties of a laminate to calculate the total cross sectional area required to support the load and safety factor.

$$\mathrm{A} = S\sigma / F \qquad (M8.2.4)$$

Dividing this value by the thickness of each ply of laminate and the width of each section, we can calculate the number of plies needed to support the load.

$$\mathrm{A} = (\mathrm{N}^* \mathrm{t})^* \mathrm{w} \quad ; \quad \mathrm{N} = \mathrm{a}/(\mathrm{t}^* \mathrm{w}) \quad (M8.2.5)$$

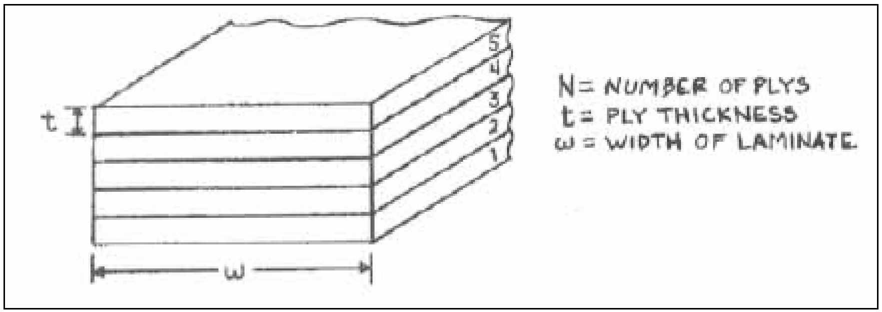


Figure M8.2.2: Bonding of number of plies

Now that we have figured out how to support basic tension and compression, what can we use to support the shear? Because any shear stress can be reduced to principal tensile and compressive stresses along the +/-45°axes, fiber reinforced laminates can also be used to effectively support this type of load.

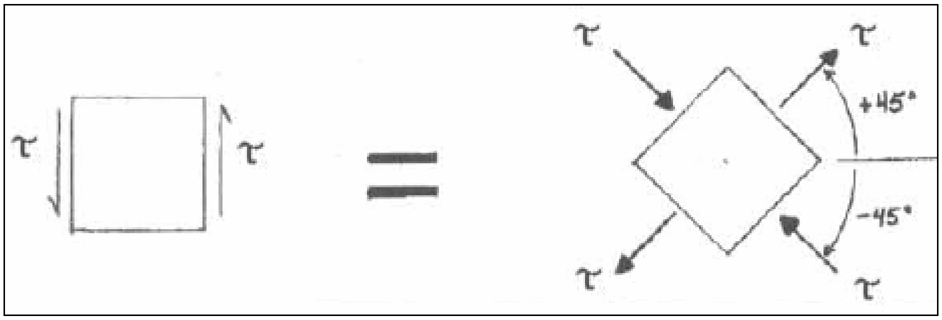


Figure M8.2.3: Shear forces acting in plane of structural composites

Since the tensile and compressive stress in this type of situation are both equal to the original value of the shear stress, the amount of fiber needed can be calculated in the same manner as described above. This is only effective if buckling is not a major concern for the thin layers of material. Another method of supporting the shear load is to separate the tension and compression members with a solid core material such as foam, wood, or honeycomb. The thickness or width is simply determined by the shear strength of the material you choose. This solution is generally best when the distance between the tension and compression sheets is small and the surface area of the part is large. For the part in Figure M8.2.1, the more ideal solution is to separate a small number of thin woven fabric sheets with a layer of solid core. Because the fibers are placed at right angles, the fabric can be rotated to orient the fibers at +/-450 to the direction of the shear load. This utilizes the high strength and low weight of the fiber reinforcement, and solves the buckling by using the sandwich style construction in the shear web. The resulting product would look something like Figure M8.2.4.

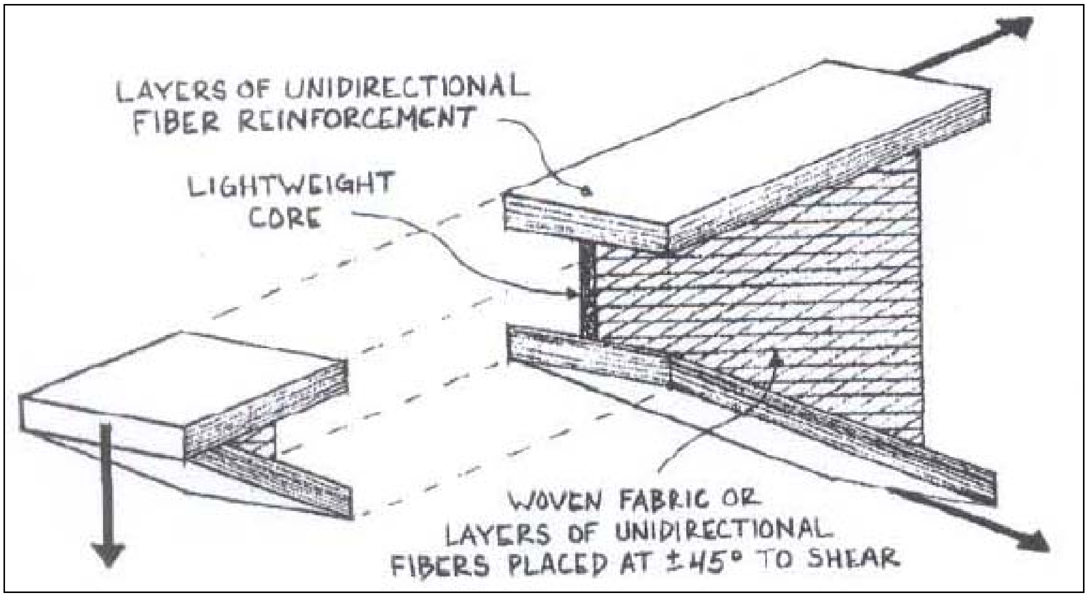


Figure M8.2.4: Final product structural composite

The last problem in this example is how to connect the weight to the end of the beam and how to attach the beam to the support structure. The obvious problem with the pin style support is that there is no longer any significant structure through which to drill the holes for the pin. The shear web was not designed to support that type of load, so we must design a better method of attachment.

A key item to keep in mind is that point loads are not practical for composites. The main advantage to building with composite materials is that a large load can be distributed over a large area, and therefore carried by a small cross sectional area of high strength fiber. One possible solution is to extend the tension/compression plies and use the resin to bond the beam to the structure. If there is a flat plane that is suitable for this purpose, the resin should have enough shear strength to support the load without requiring an excessively large bond area. The layers of material should be reduced gradually so that abrupt changes in cross sectional area can be avoided. Another possible solution is to reinforce the ends of the cap strips at the attachment points and bond a thin metallic tube or wound fiber tube into the hole. The pins transfer the load without interfering with the fibers. The inserted tube serves to distribute the load, while the additional layers of fiber reinforcement provide the added cross sectional area to support the more concentrated load. These layers must be added gradually so as to create a gradual increase in the stressed area. Adding a stack of layers one on top of the other creates a stress concentration at the edge of the stack and defeats the purpose of reinforcing the material. These simple solutions are only intended to show a few of the basic rules one should follow when concentrated loads are necessary in composite structures. The key to designing composites and especially any concentrated loads is to keep an open mind an attempt to utilize the strengths of fiber reinforced composites. To simply add enough material to support a point load defeats the purpose of using the composite in that the strength of many isotropic metals is much higher if the anisotropic properties of the fiber are not utilized. This simple example represents the basic approach one can take to optimizing a structural application with composites. More complex structures must be handled in a similar manner. First determine where the loads enter and exit the structure and determine the basic type of loading they will create throughout the part. Second, look at the direction that the loads follow through the part (load paths) so that a rough estimation of fiber directions can be obtained. Lastly, calculate the magnitude of the load and how much material is required to support that load with the necessary safety factor. Those are the basic steps for designing a small part. A larger part can be dealt with in the same manner by breaking it up into small areas and designing each section individually. During the general conceptual design phase, the design must consider that the structure will be built with composites in order for it to be optimized. This means that the usual constraints normally placed on other designs should not distract attention away from the alternatives which best utilize composite structures.

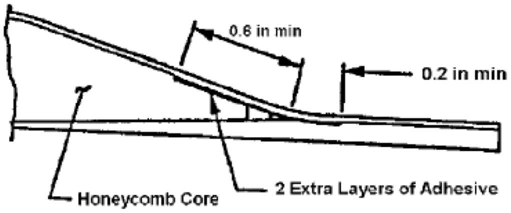
The key points that need to be emphasized are that fiber reinforced composites are not isotropic. Fibers carry loads best in tension, and compression load carrying ability is adequate. The epoxy that carries the load between the fibers is relatively light, but it is weak and the epoxy bond areas should only carry shear loads. Point loads can be dealt with, but must be designed for specifically by adding extra plies or distributing the load over a wider area.

How Construction Methods Affect Design

When designing complex three dimensional shapes for composite applications, one must consider the feasibility of producing the part. The first step in the manufacture of composite structures is to build a tool or plug that is the exact shape and dimensions as the final part. Then a mold is produced from this plug by covering it with fiberglass/epoxy or similar material. The mold is now the inverse of the outside of the plug and the composite will be built in this mold and later removed. What is left is a composite part that is the exact shape and size as the original plug with the same quality of surface finish as the inside of the mold. Generally, the plug is produced from wood or foam depending on the durability required to make the mold. One of the constraints created as a result of this type of process is that all of the draft angles between the plug and the mold, or the mold and the part, must be positive. If this requirement is not fulfilled, the plug and then the mold would have to be destroyed in the production of each part because they could not be separated. One solution to this problem is to split a complex part into pieces which do have positive draft angles. However they must be joined together later by some sort of adhesive, and such joints should only be loaded in shear and not tension. This ensures a large bond area to support the load. Another solution is to only split the mold into pieces so that the part can be produced as one solid part and the mold can be removed in sections that have only positive draft angles. This eliminates the destruction of the plug and mold and also eliminates the need to bond pieces of the final part together.

M8.2.3 Sandwich design

No.	Lesson	Reason Or Consequence
1.	Facesheets should be designed to minimize people induced damage during handling or maintenance of component.	Thin skin honeycomb structure is very susceptible to damage by harsh handling.
2.	When possible avoid laminate buildup on the core side of the laminate.	Minimizes machining of the core.
3.	Core edge chamfers should not exceed 20° (from the horizontal plane). Larger angles may require core stabilization. Flex core is more sensitive than rigid core.	Prevents core collapse during cure cycle.
4.	Use only non-metallic or corrosion resistant metal honeycomb core in composite sandwich assemblies.	Prevents core corrosion
5.	Choice of honeycomb core density should satisfy strength requirements for resisting the curing temperature and pressure during bonding or cocuring involving the core. 3.1 PCF (50 g/m3) is a minimum for non-walking surfaces.	Prevents crushing of the core.

6.	For sandwich structure used as a walking surface, a core density of 6.1 PCF (98 g/m3) is recommended.	3.1 PCF (50 g/m3) core density will result in heel damage to the walking surface.
7.	Do not use honeycomb core cell size greater than 3/16 inch (4.8 mm) for cocuring sandwich assemblies (1/8 inch (3.2 mm) cell size preferred).	Prevents dimpling of face sheets.
8.	When core is required to be filled around bolt holes, etc., this should be done using an approved filler to a minimum of 2D from the bolt center.	Prevents core crushing and possible laminate damage when bolt is installed.
9.	Two extra layers of adhesive should be applied to the inner moldline at the core run out (edge chamfer). This should be applied a minimum of 0.6 in. (15 mm) from the intersection of the inner skin and edge band up the ramp and a minimum of 0.2 in. (5 mm) from that point into the edge band.	Curing pressures tend to cause the inner skin to "bridge" in this area creating a void in the adhesive (skin to core bond). 
10.	The use of honeycomb sandwich construction must be carefully evaluated in terms of its intended use, environment, inspect-ability, reparability, and customer acceptance.	Thin skin honeycomb is susceptible to impact damage, water intrusion due to freeze/thaw cycles, and is difficult to repair.

M8.2.4 Bolted joints

1.	Design the joints first and fill in the basic structure afterwards.	Optimizing the “basic” structure first compromises the joint design and results in low overall structural efficiency.
2.	Joint analysis should include the effects of shimming to the limits permitted by drawings.	Shimming can reduce joint strength.
3.	Design joints to accommodate the next larger fastener size.	To accommodate routine MRB and repair activities.
4.	Bolted joint strength varies far less with percentage of 0° plies in fiber	The stress concentration factor, K_t, is highly dependent on 0°plies.

	pattern than does unnotched laminate strength.	
5.	Optimum single-row joints have approximately three-fourths of the strength of optimum four-row joints.	Optimum single-row joints operate at higher bearing stress than the most critical row in an optimized multi-row joint.
6.	Common errors in composite bolted joints are to use too few bolts, space them too far apart, and to use too small a diameter.	Does not maximize the strength of the laminate.
7.	Rated shear strength of fasteners does not usually control the joint design.	Bolt diameter is usually governed by the need not to exceed the allowable bearing stress in the laminate.
8.	The peak hoop tensile stress around bolt holes is roughly equal to the average bearing stress.	Keeping the laminate tensile strength high requires keeping the bearing stress low.
9.	Maximum torque values should be controlled, particularly with large diameter fasteners.	Avoids crushing the composite.
10.	Bolt bending is much more significant in composites than for metals.	Composites tend to be thicker (for a given load) and more sensitive to non-uniform bearing stresses (because of brittle failure modes.
11.	Optimum w/d ratio for multi-row bolted joints varies along length of joint. w/d = 5 at first row to minimize load transfer, w/d = 3 at last row to maximize transfer, w/d = 4 for intermediate bolts.	Maximizes joint strength.
12.	Stainless steel fasteners in contact with carbon should be permanent and installed wet with sealant.	Prevents galvanic corrosion.
13.	Use a layer of fiberglass or Kevlar (0.005 inch (0.13 mm) minimum) or adhesive with serim on faying surfaces of carbon epoxy panels to aluminum.	Prevents corrosion of aluminum.
14.	Bolt stresses need careful analysis, particularly for the effects of permissible manufacturing parameters, for example, hole perpendicularity (±10°), shimming, loose holes.	Bolt failures are increasingly becoming the “weak link” with current high strength composite materials.
15.	Bolted joint data bases should include the full range of all	Establishes that failure modes remain consistent and that there are no detrimental

	permitted design features.	interaction effects between design parameters.
16.	The design data base should be sufficient to validate all analysis methods over the entire range permitted in design.	For proper verification of analytical accuracy.
17.	Mechanical joint data bases should contain information pertaining to durability issues such as clamp-up, wear at interfaces, and hole elongation. Manufacturing permitted anomalies such as hole quality, edge finish, and fiber breakout also need to be valuated.	Practical occurrences can affect strength and durability.
18.	Use drilling procedures that prevent fiber break out on the back side of the component.	Improper back side support or drilling procedures can damage surface plies on the back side.
19.	Splice plate stresses should be lower than the stresses in skins to prevent delaminations.	Splice plates see less clamp up than the skin sandwiched in between, because of bolt bending.
20.	The best bolted joints can barely exceed half the strength of unnotched laminates.	The strength reduction is caused by stress concentrations around the hole for the fastener.
21.	Laminate percentages for efficient load transfer: 0°= 30-50%; ±45°= 40-60%; 90°= minimum of 10%.	Best range for bearing and by-pass strength.
22.	Countersink depths should not exceed 70% of laminate thickness.	Deep countersinks result in degraded bearing properties and increased hole wear.
23.	Fastener edge distance and pitch: Use 3.0D edge distance in direction of major load; use 2.5D + 0.06 side distance. (D is diameter of fastener.)	Maximizes joint strength.
24.	Gap between attached parts should not exceed 0.03 inch (0.8 mm) for nonstructural shim.	Large gaps cause excessive bolt bending, non-uniform bearing stresses, and eccentric load path.
25.	Any gap in excess of 0.005 inch should be shimmed.	Minimizes interlaminar stresses due to clamp-up.
26.	Use “form-in-place” gaskets on carbon/ epoxy doors over anodized aluminum substructure. Allow for a seal thickness of 0.010 ± 0.005 inch (-0.25 ± 0.13 mm) minimum.	Prevents corrosion of aluminum.

27.	Use only titanium, A286, PH13-8 MO, monel or PH17-4 stainless steel fastener with carbon/epoxy.	Prevents galvanic corrosion.
28.	Do not buck rivets in composite structure.	The bucking force can damage the laminate.
29.	The use of interference fit fasteners should be checked before permitting their use in design.	Installation of interference-fit fasteners can damage laminates if a loose-fit sleeve is not installed first.
30.	Fastener-to-hole size tolerance for primary structure joints must be assessed and controlled.	Tight fitting fastener promotes uniform bearing stress in a single fastener hole, and promotes proper load sharing in a multi-fastener joint.
31.	Squeeze rivets can be used if washer is provided on tail side.	Washer helps protect the hole.
32.	For blind attachments to composite substructure, use fastener with large blind side footprint of titanium or A286.	Prevents damage to composite substructure by locking collars of fasteners.
33.	Tension head fasteners are preferred for most applications. Shear head fasteners may be used in special applications only with stress approval.	Shear head fasteners.
34.	Avoid putting fastener threads in bearing against the laminate.	Fastener threads can gouge and damage the laminate.
35.	Tapered splice plates should be used to tailor the load transfer, row by row, to minimize the bearing stress at the most critical row.	Multi-row bolted joints between uniformly thick members will have high peak bearing loads in outermost rows of fasteners.

M8.2.5 Design and analysis

No.	Lesson	Reason Or Consequence
1.	"Concurrent Engineering", whereby a new product or system is developed jointly and concurrently by a team composed of designers, stress analysts, materials and processes, manufacturing, quality control, and support engineers, (reliability, maintainability, survivability), as well as cost estimators, has become the accepted design approach.	To improve the quality and performance and reduce the development and production costs of complex systems

2.	In general, design large cocured assemblies. Large assemblies must include consideration for handling and repair.	Lower cost due to reduced part count and assembly time. If the assembly requires overly complex tooling, the potential cost savings can be negated.
3.	Structural designs and the associated tooling should be able to accommodate design changes associated with the inevitable increases in design loads.	To avoid scab-on reinforcements and similar last minute disruptions.
4.	Not all parts are suited to composite construction. Material selection should be based on a thorough analysis that includes consideration of performance, cost, schedule, and risk.	The type of material greatly influences performance characteristics as well as produce-ability factors.
5.	Uniwoven and bi-directional woven fabric should be used only when justified by trade studies (reduced fabrication costs). If justified, woven fabric may be used for 45°or 0°/90°plies.	Fabric has reduced strength and stiffness properties and the prepreg material costs more than tape. Fabric may be necessary for complex shapes and some applications may require the use of fabric for its drapeability.
6.	Whenever possible, mating surfaces should be tool surfaces to help maintain dimensional control. If this is not possible, either liquid shims or, if the gap is large, a combination of precured and liquid shims should be used.	To avoid excessive out-of-plane loads that can be imposed if adjoining surfaces are forced into place. Large gaps may require testing.
7.	Part thickness tolerance varies directly with part thickness; thick parts require larger tolerance.	Thickness tolerance is a function of the number of plies and the associated per-ply thickness variation.
8.	Carbon fibers must be isolated from aluminum or steel by using an adhesive layer and/or a thin glass-fiber ply at faying surfaces.	Galvanic interaction between carbon and Aluminum or steel will cause corrosion of the metal.
9.	The inspect-ability of structures, both during production and in-service, must be considered in the design. Large defects or damage sizes must be assumed to exist when designing composite structures if reliable inspection	There is a much better chance that problems will be found if a structure is easily inspected.

	procedures are not available.	
10.	In Finite Element Analysis (FEA) a fine mesh must be used in regions of high stress gradients, such as around cut-outs and at ply and stiffener drop-offs.	Improper definition or management of the stresses around discontinuities can cause premature failures.
11.	Eliminate or reduce stress risers whenever possible.	Composite (fiber-dominated) laminates are generally linear to failure. The material will not yield locally and redistribute stresses. Thus, stress risers reduce the static strength of the laminate.
12.	Avoid or minimize conditions which cause peel stresses such as excessive abrupt laminate terminations or cocured structures with significantly different flexural stiffnesses (i.e., $EI_1 >> EI_2$).	Peel stresses are out-of-plane to the laminate and hence, in its weakest direction.
13.	Buckling or wrinkling is permissible in thin composite laminates provided all other potential failure modes are properly accounted for. In general, avoid instability in thick laminates.	Significant weight savings are possible with postbuckled design.
14.	Locating 90°and ±45°plies toward the exterior surfaces improves the buckling allowables in many cases. Locate 45° plies toward the exterior surface of the laminate where local buckling is critical.	Increases the load carrying capability of the structure.
15.	When adding plies, maintain balance and symmetry. Add between continuous plies in the same direction. Exterior surface plies should be continuous.	Minimizes warping and interlaminar shear. Develops strength of plies. Continuous surface plies minimize damage to edge of ply and help to prevent delamination.
16.	Never terminate plies in fastener patterns.	Reduces profiling requirements on substructure. Prevents delamination caused by hold drilling. Improves bearing strength.
17.	Stacking order of plies should be balanced and symmetrical about the laminate midplane. Any unavoidable unsymmetric or	Prevents warpage after cure. Reduces residual stresses. Eliminates "coupling" stresses.

	unbalanced plies should be placed near the laminate midplane.	
18.	Use fiber dominated laminate wherever possible. The [0°/±45°/90°] orientation is recommended for major load carrying structures. A minimum of 10% of the fibers should be oriented in each direction.	Fibers carry the load; the resin is relatively weak. This will minimize matrix and stiffness degradation.
19.	When there are multiple load conditions, do not optimize the laminate for only the most severe load case.	Optimizing for a single load case can produce excessive resin or matrix stresses for the other load cases.
20.	If the structure is mechanically fastened, an excess of 40% of the fibers oriented in any one direction is inadvisable.	Bearing strength of laminate is adversely affected.
21.	Whenever possible maintain a dispersed stacking sequence and avoid grouping similar plies. If plies must be grouped, avoid grouping more than 4 plies of the same orientation together.	Increases strength and minimizes the tendency to delaminate. Creates a more homogeneous laminate. Minimizes interlaminar stresses. Minimizes matrix microcracking during and after service.
22.	If possible, avoid grouping 90°plies. Separate 90°plies by a 0°or ±45°plies where 0°is direction of critical load.	Minimizes interlaminar shear and normal stresses. Minimizes multiple transverse fractures. Minimizes grouping of matrix critical plies.
23.	Two conflicting requirements are involved in the pairing or separating of ±θ° plies (such as ±45°) in a laminate. Laminate architecture should minimize interlaminar shear between plies and reduce bending/ twisting coupling.	Separating ± θ° plies reduces interlaminar shear stresses between plies. Grouping ± θ° plies together in the laminate reduces bending/twisting coupling.
24.	Locate at least one pair of ±45° plies at each laminate surface. A single ply of fabric will suffice.	Minimizes splintering when drilling. Protects basic load carrying plies.
25.	Avoid abrupt ply terminations. Try not to exceed dropping more than 2 plies per increment. The plies that are dropped should not be adjacent to each other in the laminate.	Ply drops create stress concentrations and load path eccentricities. Thickness transitions can cause wrinkling of fibers and possible delaminations under load. Dropping non-adjacent plies

		minimizes the joggle of other plies.
26.	Ply drop-offs should not exceed 0.010 inch (0.25mm) thick per drop with a minimum spacing of 0.20 inch (0.51 mm) in the major load direction. If possible, ply drop-offs should be symmetric about the laminate midplane with the shortest length ply nearest the exterior faces of the laminate. Shop tolerance for drop-offs should be 0.04 inch (1 mm).	Minimizes load introduction into the ply drop-off creating interlaminar shear stresses. Promotes a smooth contour. Minimizes stress concentration.
27.	Skin ply drop-offs should not occur across the width of spars, rib, or frame flange.	Provides a better load path and fit-up between parts.
28.	In areas of load introduction there should be equal numbers of +45° and -45° ply on each side of the mid-plane.	Balanced and symmetric pairs of ±45° plies are strongest for in-plane shear loads which are common at load introduction points.
	A-29.A continuous ply should not be buttspliced transverse to the load direction.	Introduces a weak spot in the load path.
30.	A continuous ply may be butt-spliced parallel to the load direction if coincident splices are separated by at least four plies of any orientation.	Eliminates the possibility of a weak spot where plies are butted together.
31.	The butt joint of plies of the same orientation separated by less than four plies of any direction must be staggered by at least 0.6 inch (15 mm).	Minimizes the weak spot where plies are butted together.
32.	Overlaps of plies are not permitted. Gaps should not exceed 0.08 inch (2 mm).	Plies will bridge a gap, but must joggle over an overlap.

Learning Unit-3: M8.3

M8.3 Software for Composite Materials Design

Laminate Analysis/Design Software for Composite Materials Design

This is a partial list of software available for Composite Material Analysis and Design. Listed costs are just estimates based on information on the web.

- **ASCA**- Automated System Composite Analysis
- **BMI3** Buckling Mode Interaction of Composite Shells (free).
- **CADEC** Computer Aided Design Environment for Composites (free to qualified users).
- **CompositePro** for Windows
- **CompSAE.** Micromechanics and Structural Analysis.
- **CShell.** Boat Design.
- **DYNA-3D.** General Purpose Finite Elements. Support on User Materials.
- **ESAcomp.** Laminate software
- **FiberSIM.** Needs CAD system: CATIA, Pro/Engineer.
- **HyperSizer.** Optimization/Analysis based on FE model.
- **Lusas** Composite. Finite Element program based on General Purpose FE.
- **Promal.** Complements textbook (Free with book).
- Think Composites. Mic-Mac Templates, Genlam, Lamrank
- V-Lab. Material, laminate and bonded analysis.

Other Useful Applications

Other applications that might be useful to view class notes on the web or on a cd are:

- **NB Viewer:** A viewer for files containing Math. (Free)
- **Acrobat Viewer:** The best software to view PDF files (Free)
- **MikTeX:** LaTeX installation for Windows and Linux.
- **WinEdt:** The best Windows editor for LaTeX.
- **JabRef:** The best Reference Manager for LaTeX, free, platform independent, downloads
  references directly from E-Village, etc.
- **GSview:** Converts PS to EPS and more... Needs Ghostscript.
- **Pstoedit:** Install to enable GSView to convert PS, PDF, to vector format.
- **Ghostscript:** PS and PDF interpreter, graphics and filtering routines.
- **Basic LaTeX instruction manual**
- **Easy Way to make eps file for LaTeX**
- **Advanced LaTeX instruction manual**

Learning Unit-4: M8.4

M8.4 Composite Codes and Standards

M8.4.1 Composite Codes

M8.4.1.1 Committees

A number of committee activities from professional organizations are addressing the recommended use and specification of FRP composites. Many organizations have published codes, standards, test methods and specifications for FRP composites and their products for the respective products. For example in the FRP pipe market, design standards, test methods, and recommended practices were published by the American Petroleum Institute (API), American Society of Mechanical Engineers (ASME), American Water Works Association (AWWA), Underwriter Laboratories (UL), and others. In the corrosion resistant structural equipment market, ASME published an industry standard called RTP-1. In RTP-1, the document provides purchasers of corrosion-resistant composite equipment with guidelines for the specification of high-quality, cost-effective and high-performance equipment. The American Society of Testing and Materials (ASTM) published recognized industry test methods for FRP composites used in all markets.

Organization	**Committee**
American Concrete Institute (ACI)	▪ 440 – Composites for Concrete ▪ 440C – State-of-the-art-Report ▪ 440D – Research ▪ 410E – Professional Educations ▪ 440F – Repair ▪ 440G – Student Education ▪ 400H – Reinforced Concrete (rebar) ▪ 440I – Prestressed Concrete (tendons) ▪ 440J – Structural Stay-in-Place Formwork ▪ 440K – Material Characterization ▪ 400L - Durability
American Society of Civil Engineers (ASCE)	Structural Composites and Plastics
American Society of Testing and Materials (ASTM)	▪ ASTM D20.18.01 – FRP Materials for Concrete ▪ ASTM D20.18.02 – Pultruded Profiles ▪ ASTM D30.30.01 – Composites for Civil Engineering
AASHTO Bridge Subcommittee	T-21 - FRP Composites
International Federation of Structural Concrete (FIB)	Task group on FRP
Canadian Society of Civil Engineers (CSCE)	ACMBS – Advanced Composite Materials for Bridges and Structures
Japan Society of Civil Engineers	Research Committee on Concrete Structures with Externally Bonded Continuous Fiber

	Reinforcing materials
Transportation Research Board	A2C07 – FRP Composites

For almost twenty years, the American Society of Civil Engineers (ASCE) has operated a technical committee called Structural Composites and Plastics (SCAP) to address the design and implementation of composites. This committee published a design manual in the early 1980's and is currently working to update this manual to address the many FRP composite products developed over the years.

The American Concrete Institute, and its Committee 440 with ten different subcommittees, address FRP composites in concrete in such topics as state-of-the-art, research, professional and student education, repair, rebar, prestressing, and stay-in-place structural formwork. These highly active committees are focused to produce guidance documents for the engineer. In particular, ACI 440F is developing a document titled "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures". This landmark publication reviews the state-of-the-art, provides guidelines for application and selection, design recommendations, and construction techniques for the use of FRP materials to repair, strengthen, or upgrade concrete structures. The ACI 440H committee is developing a similar document of FRP rebar titled "Guide for the Design and Construction of Concrete Reinforced with FRP Bars". The proposed guideline reviews knowledge based on research and field applications of FRP bars worldwide.

Several ASTM committees are currently working on consensus test methods for the use of rebars, repair materials, and pultruded structural profiles. In ASTM D20.18.01 (FRP Materials for Concrete) committee, industry experts are addressing materials and products to develop standard test methods for FRP rebar and repair materials. In ASTM D20.18.02 is a committee focused on the development of test methods for FRP pultruded profiles and shapes. The ASTM D30.30.01 (Composites for Civil Engineering) committee addresses FRP composites products used construction.

The American Association of State Highway and Transportation Officials (AASHTO) Bridge Committee established a subcommittee in 1997 called "T-21 Composites". This committee has an ongoing effort to develop design guidelines for of the use of composites in bridge applications including FRP reinforced concrete, concrete repair, and vehicular bridge deck panels.

M8.4.1.2 Organizations

The Civil Engineering Research Foundation (CERF), the research arm of the American Society of Civil Engineers is actively engaged with technology transfer of new cutting edge technologies. One of CERF's programs, Highway Innovation Technology Evaluation Center (HITEC), coordinates product evaluations between the end-user community and industry to produce highway products that meet the needs of the end-user with the program results being shared with all State DOT bridge departments. HITEC has provided the civil engineering community with several product evaluation programs that address the use of composites. One program in particular, FRP Composite Bridge Decks, has developed an evaluation plan for several composites bridge manufacturers for testing, design, and performance of bridge deck panels manufactured with FRP materials.

The Intelligent Sensing for Innovative Structures (ISIS) of the Canadian Network of Centers of Excellence was established to advance civil engineering to a world leadership position through the development and application of FRP composites and an integrated intelligent fiber optic sensing technology to benefit all Canadians through innovative and intelligent infrastructure. ISIS Canada, through its universities, has coordinated a team of professionals dedicated to advancing technology by building better roads, buildings, and bridges. ISIS has
many research projects and field evaluations under study that demonstrate successful implementation of FRP composites with validated design and testing as well as techniques to document the in-field service of new products and systems. ISIS Canada is credited with building the first smart sensing FRP composite bridge and continues to make advancements in the areas of concrete repair, bridge construction with FRP rebars and tendons, and roadways.

Several professional societies from around the world have published design codes for FRP Rebar. In Canada, the civil engineers have documented design procedures in the Canadian Highway Bridge Design Code for the use of FRP rebars. The Japan Society of Civil Engineers has published a code that provides design recommendations for the use of FRP rebars and tendons.

M8.4.2 Standards Development

Several global activities are taking place to implement FRP composites materials and products into respective design codes and guidelines. The following summarizes this activity:

Code/Standard	Reference
Canadian Building Code	Design and Construction of Building Components with Fiber Reinforced Plastics
Canadian Highway Bridge Design Code (CHBDC)	Fiber Reinforced Structures (section of code)
International Conference of Building Officials (ICBO)	AC 125: Acceptance Criteria for Concrete and Unreinforced Masonry Strengthening Using Fiber-Reinforced Composite Systems
Japan Society of Civil Engineers (JSCE) Standard Specification for Design and Construction of Concrete Structures	Recommendation for Design and Construction for Reinforced Concrete Structures Using Continuous Fiber Reinforcing Materials

In April 1997, The International Conference of Building Officials (ICBO) published AC125 “Acceptance Criteria for Concrete and Unreinforced Masonry Strengthening Using

Fiber-Reinforced Composite Systems”. ICBO has also published individual company product evaluation reports on FRP systems used to strengthen concrete and masonry structural elements such as columns, beams, slabs, and connections of wall to slab.

M8.4.2.1 Technology Transfer

Many academic institutions in the North America, as well as around the world are actively engaged in research involving FRP applications for civil infrastructure. Several universities have distinguished themselves as centers of excellence in specific fields of expertise. Universities and State Departments of Transportation often collaborate on the evaluation and implementation of FRP composites that best meet the needs of the State.

Organization	Activity
American Society of Civil Engineers	Journal of Composites for Construction
Federal Highway Administration (FHWA)	TEA-21 Innovative Bridge Research and Construction Program (IBRC)
Intelligent Sensing for Innovative Structures (ISIS) of the Canadian Network of Centers of Excellence	Industry research and collaboration FRP International (global newsletter)
Market Development Alliance of the FRP Composites Industry	Project Teams and Programs geared towards development of FRP composites for construction applications

The Fed Federal Highway Administration (FHWA) through the TEA-21 Innovative Bridge Research and Construction Program (IBRC) has provided new construction materials the opportunity to meet the goals of reducing maintenance and life-cycle costs of bridge structures. Funds are provided for the Federal share of the cost for repair, rehabilitation, replacement, and new construction of bridges using innovative materials. Each year since the first solicitation in 1998, FRP composites led other innovative construction materials for funding to demonstrate the unique benefits being sought by FHWA to build a better and long-lasting infrastructure.

Many societies, trade associations, academic institutions and organizations worldwide host periodic conferences, trade shows, and seminars in forums that educate as well as transfer state-of-the-art technology to end-users. Some of the conferences are listed below:

- ACMBS Advanced Composites Materials for Bridges and Structures (Canada)
- ASCE Construction and Materials Congress
- PORTS, every three years (2001, 2004)
- Structures Congress
- American Composites Manufacturer's Association (formerly Composites Fabricators Association -CFA) annual conference and exposition, early fall
- FRPRCS Fiber-Reinforced Polymers for Reinforced Concrete Structures (International)
- IBC International Bridge Conference, annual, June
- ICCI International Conference on Composites for Infrastructure
- SAMPE Society for the Advancement of Material and Process Engineering, annual conference and exposition, late spring/early summer.