Chapter 7
Engineering Guidance

7-1. Manufacturer's Guidelines

Many commercial FRP products are designed by FRP suppliers to suit their own processing capability and their unique applications experience. There is some limited standardization of available sizes, but almost no standardization of properties. Some manufacturers publish their own test results and design guidelines. In the absence of a national design standard, such information is valuable to the design engineer. However, the designer must recognize that such guidelines may reflect results obtained from limited applications and processes. The same guidelines may not be suitable for a different application or another manufacturer's process. Since federal procurement regulations usually prohibit sole-source procurement, the designer will usually not know which supplier will produce the FRP. When the designer is relying on manufacturer's data to determine the adequacy of a composite material, the specification should require certification of material properties by the manufacturer.

7-2. Military Handbooks

Military Handbooks are available which discuss the design and analysis of composite materials as well as quality assurance and generation of property data. Many of these documents were intended for use on aircraft and aerospace vehicles and combat vehicle applications but the information presented is not limited to these applications. Some of these handbooks are discussed below.

a. Military Handbook, MIL-HDBK-17-1D. MIL-HDBK-17-1D, "Polymer Matrix Composites; Volume 1, Guidelines," focuses on characterization of fibers, matrix materials, and laminates and evaluations of prepreg, joints, and notched/damaged laminates. Chapter topics include objectives in generating property data, evaluation of reinforcement fibers, matrix characterization, prepreg materials characterization, lamina and laminate characterization, structural element characterization, and the analysis and presentation of data.

b. Military Handbook, MIL-HDBK-17-3D. MIL-HDBK-17-3D, "Polymer Matrix Composites; Volume III, Utilization of Data," discusses processes, quality control, and design and analysis. Topics are also included on behavior of structural joints, structural reliability, thick-section composites, and design for repair.

c. Military Handbook, MIL-HDBK-1002/6. MIL-HDBK-1002/6, "Aluminum Structures, Composite Structures, Structural Plastics and Fiber-Reinforced Composites," contains design information for fiberglass-reinforced plastics, thermoplastics, and glass-fiber-, steel-fiber-, and organic-fiber-reinforced concrete. Numerous references are provided as design standards and guidelines, and an appendix includes information on desirable characteristics, limitations and design cautions, and quality control.

7-3. Design Approach

Design with composite materials is different from design with traditional isotropic materials. It is important to take advantage of the anisotropic behavior that is intrinsic with fiber-reinforced composite materials. Several different theories can be used when designing with composite materials. Some of them are the maximum stress theory, the maximum strain theory, and the Tsai-Wu quadratic interaction theory. Fracture mechanics approaches are also commonly used in the design process. These approaches are described in composite materials textbooks, such as those by Gibson (1994) and Ashbee (1993). However, structural design engineers in the Corps are usually not familiar with actual design of FRP members. Therefore, when FRP components are used in a project, the USACE engineer will prepare a procurement specification for the component, which will then be designed by a subcontractor or the FRP supplier.

a. Performance specification. The typical USACE approach to design with composite materials is to utilize performance specifications, rather than designing from component material properties. In this situation, the supplier would need to furnish a structural component that would perform in a particular manner, but the details of how this was to be achieved would be left to the supplier. An example of this is the design of the composite wicket gate by the Louisville District. An example of a performance specification is given in Appendix C.

b. Material selection.

(1) Evaluate application. Material selection is more complicated than it is with traditional materials. The processing of the material greatly influences the properties of the fabricated component, which will then change its potential applications. Any time the application is changed, both the base materials and their processing need to be re-evaluated. Since the processing (and fabrication) of composite structure affects its properties, the designer

must include the processing and fabrication effects on properties during the design phase.

(2) Economical considerations. Composite materials that produce the least expensive structure commensurate with good design should be used. The designer is trying to produce the lowest cost structure. Usually this means that the lowest cost fiber, glass, will be used. A glass-fiber-based composite is likely to be the cheapest on a per pound basis. However, the designer should note that a carbon-based composite will be stiffer than glass-based ones with the same area. Therefore, if the application is controlled by stiffness, carbon composites may be more cost-effective in some cases. In another situation, if the structure needs to have a significant amount of ductility, an aramid-type composite may be the only one that really meets this requirement.

c. Standard components. One way to save costs in both design and fabrication is to use simple components that are repeated wherever necessary. For example, the designer might design the skin plate of a gate to be made of a set of standard sized composite plates. In this manner the small panels could be easily fabricated and shipped. They could then be attached at the project site. Using standard components would also make it easier to replace broken or damaged parts at the site. Some specific shapes can allow for prebuilt components, such as a honeycomb panel, to be used.

7-4. Connections

Components of a composite structure are usually joined by either mechanical or adhesive joints. No national joint design standards for FRP's now exist. Therefore, each prospective type of joint should be tested before use to ensure that it will carry the required loads. Various types of mechanical joints have been created and are discussed below. The adhesive joint bonds the two parts chemically by some type of adhesive. This joint will be as strong as the matrix material (since many matrix materials are themselves some type of epoxy) but not as strong as the structure itself. Combinations of mechanical and adhesive joints can be used in some applications.

When planning the layout of the structure's components, compressive joints are preferable. Elimination of tension connections through larger parts may be used to assist in achieving compressive joints. Since failure often occurs at a joint, a structure with fewer joints is likely to be stronger. For example, consider the manufacture of a triangular-shaped box beam, a structural element that could be used in many applications. One method of construction would be to make three flat panels, and then join them by some type of bonding method. An alternate would be to create a triangular-shaped mold, and then create the structure as inherently one composite piece. The unidirectional layers can then be wrapped around the entire structure, thereby providing fiber reinforcement at what otherwise would have been the joints between different plates. These joints then will be virtually as strong as the composite structure itself.

a. Mechanical joints.

(1) Mechanical joints usually have some type of bolt holding together the different pieces of the structure. Examples of three different types of bolted joints are shown in Figures 7-1 through 7-3. Figure 7-1 shows a single lap joint. This is the simplest type but has the disadvantage that it tends to twist when an in-plane load is applied to either of the two plates. The double lapped bolted joint (shown in Figure 7-2) will not twist, but it is more complicated. Figure 7-3 shows a strapped bolted joint. The strength of this joint depends upon the strength of the strapping, the strength of the bolt, and the strength of the composite.

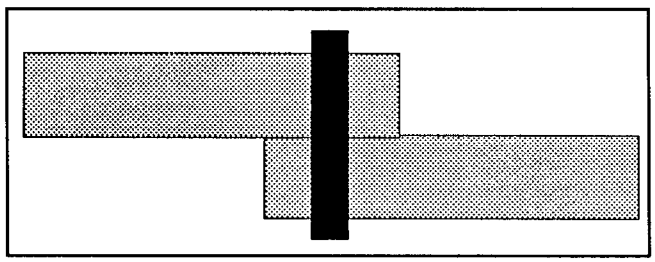

Figure 7-1. Single lap bolted joint

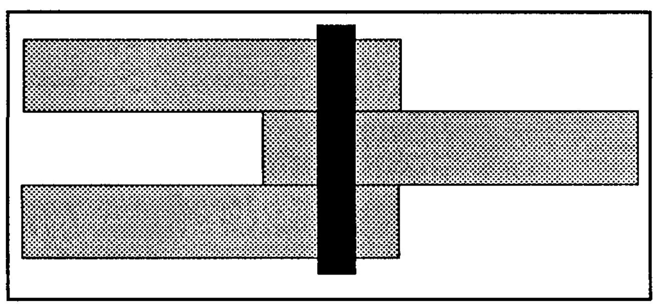

Figure 7-2. Double lap bolted joint

(2) In each of these bolted joints, the holes made in the composite plates should be coated if the joint is to be exposed to water. This coating will help to avoid water absorption through the joint region. Typically the bolts

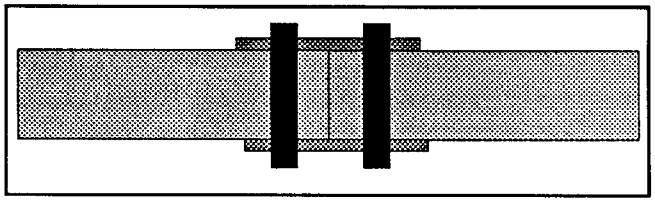

Figure 7-3. Strapped bolted joint

themselves will be made from a traditional metallic material, such as stainless steel or monel.

(3) Mechanical joints have two advantages over adhesive joints. They are frequently not as susceptible to environmental damage and they are easy to disassemble and reassemble, making it easier to perform quality control inspections and to replace damaged plates without having to replace the entire structure.

(4) There are three major disadvantages of mechanical joints. The first is that the joint is frequently less stiff than the base plates it is connecting. Another major disadvantage is that the creation of the bolt holes can produce small cracks in the vicinity of the hole. These cracks can act to create large concentrated stresses near the hole, which could result in premature failure of the system. Another disadvantage of using bolted joints is that the ply orientation lay-up near the bolt hole may need to be modified so as to avoid the problem of fiber pull. Whenever installation procedures require cutting through the reinforcement fibers of the composite, additional considerations must be given. A hole cut through the composite system, for example as part of a joint connection, will cut the reinforcing fibers and produce a weak joint at that location. The exact effect of the hole depends on the fiber orientation at the location of the hole as well as the location of the hole relative to the edge of the component.

(5) One way to strengthen mechanical joints is to add more material to them, so that a larger force is needed to break the system. An example is shown in Figure 7-3 for a strap bolted joint. The strapping material's strength is what holds the joint together. It can frequently be of some material other than a composite. Additional ways to strengthen mechanical joints are to make the regions in the vicinity of the bolt thicker than the base plates, thereby reducing the stress in the joint and allowing it to carry a higher load.

b. Adhesives.

(1) An adhesive joint is one in which some type of adhesive material is placed between the two plates that are to be attached together. Most adhesives are able to withstand shear loading more than tensile loading. This means that if adhesives are used, they should not be designed for use in tension. Examples of adhesively bonded joints are shown in Figures 7-4 through 7-6. These joints are the same basic three shapes that were discussed under mechanical joints, except that bolts have been replaced by the adhesive material. As was discussed before, double lap bonded joints are preferable to single lap bonded joints because the tendency to twist has been reduced.

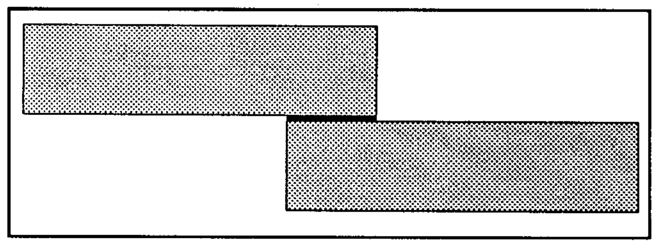

Figure 7-4. Single lap bonded joint

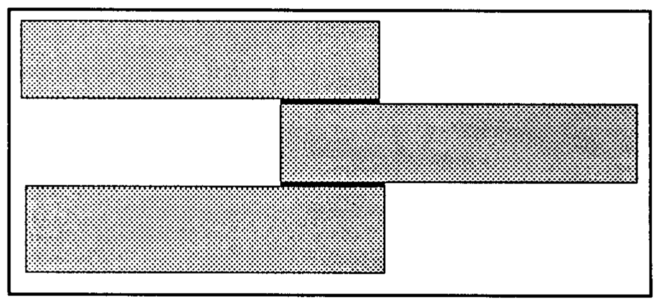

Figure 7-5. Double lap bonded joint

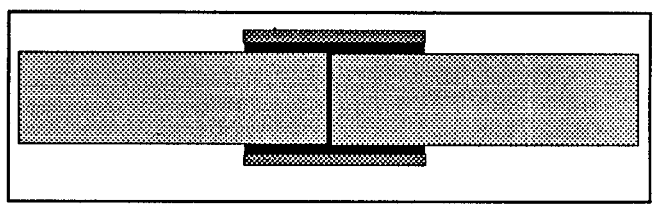

Figure 7-6. Strapped bonded joint

(2) Figure 7-6 shows a strap bonded joint. In this type of joint the adhesive holds the materials together at their ends, and also holds the plates to the strapping material. Most of the load is carried by the strapping material and the adhesive that bonds the strapping to the plates. The strength of this joint is some function of the strength of the adhesive and the strapping material.

(3) One common design issue that might be faced by engineers using composite materials to design gates would be the attachment of the skin plate to the supporting beams behind it. One method of doing so is shown in Figure 7-7. This might be considered a type of strap joint, except that the strapping material is itself an integral part of the structure. A box girder is shown in this figure since it would be more practical for composite structures.

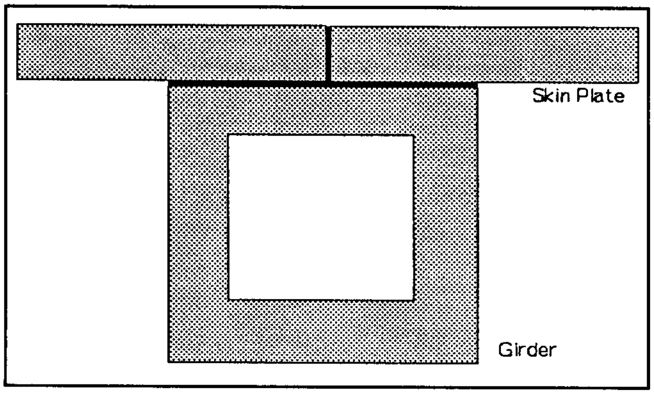

Figure 7-7. Example of an adhesive joint that is a partially lapped joint and a partially strapped joint

(4) Adhesive-bonded joints are typically stiffer than mechanical joints, because in lapped or strapped bonded joints there can be a very large surface area on which to bond. However, anything that can damage the composite resin will also damage the adhesive in the same manner. It is not possible to state that mechanical joints or adhesive joints are always superior. Which one is superior depends upon the specific application.

(5) Another approach is to use adhesive joints in a manner analogous to the welding of metals. In thermoplastic-based composites the plates can be welded together by applying a localized heat at the interface. As the resin partially melts, and then resolidifies, a very strong joint can be created. For thermoset-based composites (such as ones based on epoxies), such welding techniques cannot be used.

c. Using anchors for prestressing.

(1) FRP materials have been studied for use as prestressing tendons in prestressed concrete. To date, demonstration projects using concrete beams pretensioned and posttensioned with FRP tendons have been conducted in the United States, Europe, and Asia. Carbon-, aramid-, and glass-fiber-reinforced plastic tendons have been used in these demonstrations. These materials are well suited to the process of prestressing because of their lower modulus of elasticity. Even though the tendons experience greater strains in reaching the applied level of prestress, the lower modulus works to the advantage of the beam through lower prestress loss after locking off the stress.

(2) Despite the suitability of FRP to prestressing applications, care must be taken with anchorage devices. Due to their anisotropic nature, FRP tendons have great longitudinal tensile carrying capacity, but very low shear capacity. Consequently, loading FRP composites perpendicular to the longitudinal axis can cause failure at very low loads. This is precisely the loading condition that occurs when tendons are gripped with conventional anchors or grips that pinch the tendon to apply the prestressing loads.

(3) Wedge-type grips that rely on pinching the FRP generally are unsuitable as anchors or loading grips. These devices apply lateral load along the length of the tendon or the grip with the greatest shear loading at the mouth of the grip. The high lateral loadings in these areas can fail the tendons in shear long before the longitudinal, tensile-carrying potential of the material is realized.

(4) In the case of pretensioning where the grips are only used to apply the pretensioning load, the greatest danger caused by failure is personal injury that might occur during the prestressing operation. If sufficient care is taken in choosing the anchor, the lateral stresses on the tendon will be minimized and the tendon will not fail. As soon as the concrete has hardened around the tendon, these anchor stresses can be removed. However, in the posttensioning technique, where the anchor and its accompanying loads become part of the permanent loading configuration, the danger is always present that the shear loads could fail the tendon at some future time when the tendon is in service.

(5) For these reasons, special anchorage devices have been developed which minimize the lateral loads that

grips put on the FRP tendons. There are a number of suitable designs which have been employed. They fall into two categories, potted and wedge designs. The potted designs consist of placing the FRP tendon inside a steel collar, and filling the collar with a polymer resin to anchor the tendon inside the collar. In most of these designs, the inside surface of the collar is tapered as in a conventional wedge anchor such that the tension on the tendon will try to seat the polymer wedge into the collar. There have been several attempts to find the shape which minimizes the stress on the tendon. These range from a pipe collar with a constant inside diameter to a collar with a parabolic-shaped inside surface. Other designs are the wedge type. These differ from the conventional steel wedge designs either through the use of polymer wedges or some sort of protective sleeve around the tendon which will help distribute the stresses such that concentrations are minimized.

(6) The results of tests on ten different FRP anchor systems conducted for the Corps (Nanni et al. 1994) indicated that:

- Potted resin anchors performed better than wedge-type anchors for sustaining prestress load.

- Wedge anchors generally caused some sort of damage to the tendon.

- Some sort of grit applied to the tendons is necessary to ensure proper anchorage with wedge anchors.

- All types of anchors had problems resisting failures in tests of the tendons to failure.